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MEASUREMENT OF CRITICAL DIAMETER, SHOCK AND IMPACT SENSITIVITY OF A SPECIAL PROPELLANT

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The results of an experimental investigation of the critical diameter, and shock and impact sensitivity of the LOVA-X1A propellant are described. The detonation velocity was determined as a function of charge diameter for the propellant. The critical diameter lies between 0.245 and 0.375 in. for the bare charge. The shock sensitivity for initiating detonation in the propellant was determined by a gap test technique. The results, together with the results of projectile impact tests on solid disks of the propellant determined earlier, are discussed and examined in terms of the sensitivities of materials given in the literature.

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The critical initiating shock pressure and critical ignition energy are estimated. It is shown that the LOVA-X1A propellant is relatively insensitive to initiation compared to most cast explosives and propellants in use today. The sensitivity of stacked small grains of the propellant to projectile impact was also determined. The tests showed that the response of the grains at a large projectile diameter was always deflagration; whereas at small diameters no sustained reaction was produced. No detonation was produced by the impact. Recommendations for additional studies are given.

ACKNOWLEDGEMENT

The authors wish to acknowledge the discussion and assistance given them by the Contract Project Officer, Dr. Joseph J. Rocchio of the Ballistic Research Laboratory, who also provided the propellant samples used in the studies.

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SUMMARY

This report describes the results of an experimental investigation, whose purpose was to measure the critical diameter and shock and impact sensitivity of a special propellant of interest to the Army.

The tests were conducted on the LOVA-X1A propellant, which is made up of 75 wt % small grained HMX explosive in a polyurethane binder. The detonation velocity of bare cast cylinders of this propellant was measured as a function of charge diameter over the diameter range of 0.245 to 1.5 in. (the 0.245 and 0.375 in. charges were extruded). Detonation propagated in the bare 0.375 in. diam. charges, did not propagate in the bare 0.245 in. charges, and propagated occasionally in heavily cased, 0.245 in. charges. The critical diameter of the bare charge thus lies between 0.245 and 0.375 in., and should be closest to the latter value. The detonation characteristics of the propellant charges are discussed.

The shock sensitivity of the propellant to detonation was measured with a slightly scaled-up version of the small scale gap test (SSGT) apparatus developed at NOL (the charge diameter in the standard SSGT apparatus is less than the critical diameter of the propellant). A gap thickness corresponding to 1.869 mm of Plexiglas for 50% probability of initiation in the SSGT apparatus was found. This corresponds to an incident (in the gap material) initiation pressure of 123.6 kbar for the LOVA-X1A propellant, and is significantly larger than is required for initiating most propellants and cast explosives in use today. The LOVA-X1A propellant is thus much less sensitive to initiation than these materials. An investigation of the sensitivity of the propellant to projectile impact that was conducted on another program is also summarized; the results are compared with those from the card gap test and discussed. Estimates are made of the critical initiating shock pressure and critical ignition energy. The results all show that the LOVA-X1A propellant is relatively insensitive to initiation to detonation compared with most cast explosives and propellants in use today.

The sensitivity of stacked small grains of the propellant (confined in a wood and plastic box with a cellophane front) to projectile impact was also determined. These tests showed that the response of the grains at a large projectile diameter was always deflagration (not detonation) up to the highest velocities studied, and there was no evidence of any pressure buildup. At small projectile diameters there was little evidence of any sustained reaction being produced by the impact. These results differ from relatively large single disks of the propellant, which at a sufficiently high impact velocity undergo detonation at all of the projectile diameters used in the studies. The disks also undergo deflagration at the large projectile diameter (but not the smaller diameters) and the impact velocity threshold for this to occur is lower than for inducing detonation in the propellant. These results indicate that the stacking of grains does not seem to sensitize the material to detonation (or deflagration). However, other factors (not studied) can also be of importance with respect to this statement.

The report concludes with a brief summary of some further studies that could usefully be conducted to further understand and determine the safety aspects (with respect to detonation or a deflagration to detonation transition) of the LOVA-X1A propellant, and other composition propellants of the LOVA-type.

SECTION 1

INTRODUCTION

The vulnerability of the ammunition propellant contained in weapons systems to various types of external ignition stimuli is well known,[1] and is of considerable importance in the field use of the ammunition. For example, it has been shown that in large gun (e.g., cannon) ammunition, the cased propellant is usually more vulnerable than the associated explosive warhead.[2] The problems encountered in propellant vulnerability have consequently resulted in an effort by the Army to develop new propellants which are significantly less sensitive to various types of external ignition stimuli than are the conventional single, double and triple base formulations.

The development of relatively insensitive propellants that are suitable for practical weapons use is difficult, however, due to problems with ballistic performance (burn rate, gun ignition) and mechanical properties which often arise simultaneously with desensitization. Consequently, during the early stages of development of a propellant, the sensitivity and ballistic properties are usually only evaluated in a preliminary manner in order to determine whether the concept is viable, and further testing and development are warranted. More detailed studies then need to be conducted only on those formulations which show sufficient promise of becoming suitable for practical use.

One formulation which has successfully passed through the initial stage of development for a particular application is known as the LOVA-X1A propellant (LOVA meaning low vulnerability ammunition).[3] This propellant is composite in nature, and consists of small grained HMX explosive embedded in a polyurethane binder. Preliminary experimental and computational ballistics data indicated that this propellant can match the performance of conventional (M6 or M30) propellant, and some vulnerability tests showed it to be significantly less vulnerable than the conventional proppellants.[3] The vulnerability studies were preliminary in nature, and included high velocity fragment and shaped charge impact tests on cased propellant, and also hot wire ignition tests on the cased propellant. In addition, thermogravimetric and hot fragment initiation tests were conducted on bare propellants, as was also the standard drop weight test.

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1 Reeves, H.J. and Vikestad, W.S., "General Principles for Vulnerability Reduction of a Main Battle Tank," BRL-MR-2321, August 1973. (AD #914067L)

2. Collis, D. L., Forster, J. J., and McLain, J.P., "Vulnerability of Propellant-Filled Munitions to Impact by Steel Fragments," BRL-CR-65, March 1972. (AD #893651L)

3. Rocchio, J. J., Reeves, H. J., and May, I. W., "The Low Vulnerability Ammunition Concept-Initial Feasibility Studies," BRL-MR-2520, August 1975. (AD #B006854L)

The preceding results were quite encouraging and indicated that the basic LOVA-X1A propellant formulation may have the potential for practical use in certain real weapons systems. In order to further evaluate this potential however, and determine the optimum propellant compositon for use, additional studies were required. With regard to the vulnerability aspect of the problem, the preceding data indicated that the thermal and non-detonative impact response of the LOVA-X1A propellant is clearly superior to that of conventional propellants when subjected to external ignition stimuli. However, the propensity of the propellant towards detonation had not been defined, and required the next attention.

This report then, describes the results of an investigation whose purpose was to determine the detonation behavior of the LOVA-X1A propellant when subjected to strong shock and impact under various conditions. The studies centered around three major aspects of the problem which will be described in the following sections, viz, the critical diameter and detonation characteristics of the propellant, the shock impact sensitivity of the propellant as measured by a gap test, and the sensitivity of stacked grains of the propellant to strong projectile impact. In addition, the results of extensive studies of the projectile impact ignition of larger discs of the LOVA-X1A and three conventional propellants that were obtained on another program are summarized and used in the discussion.

SECTION 2

CRITICAL DIAMETER AND DETONATION MEASUREMENTS

2.1 General Considerations

The critical diameter of an explosive charge is the minimum diameter of an end-initiated cylinder of the charge that will just allow a steady (non-fading) detonation to propagate in the charge. In any smaller diameter charge, the initiated reaction fades (dies-out).

The general effect of the charge diameter, d, on the detonation velocity, D, of an explosive is shown in Fig. 1. At a sufficiently large charge diameter for a particular explosive, the detonation velocity is independent of diameter and is the ideal velocity, D_i, whose value depends only on the specific energy released by the detonation (heat of detonation) and the charge density. At smaller charge diameters the detonation velocity is less than the ideal value and decreases with a decrease in diameter. The detonation is then said to be nonideal. The velocity decreases because the energy loss from the chemical reaction zone where the energy is liberated (and which also drives the detonation front) becomes relatively larger, due to the greater effect which lateral gas expansion (rarefaction) has on reducing the reaction pressure. At a sufficiently small value of charge diameter (the critical diameter), the lateral energy loss becomes sufficiently large that the detonation just barely undergoes self-propagation in the charge. At smaller diameters the reaction will not propagate itself and if initiated it will die-out (the critical diameter of a confined (cased) charge is smaller than that of a bare charge).

The decrease in detonation velocity with decreased charge diameter is related to the energy release rate in the detonating explosive. For example, according to the theory of Eyring et al[4] the detonation velocity, D, at charge diameter, d, is related to the ideal detonation velocity, D_i, and the reaction zone length, a, by the equation

$$\frac{D}{D_i} = 1 - \frac{a}{d} \qquad (1)$$

This equation indicates that the detonation velocity should decrease linearly with 1/d if the reaction zone length is constant, and this general behavior is usually observed experimentally over the lower range of 1/d, as illustrated in Fig. 1. However, at sufficiently small values of d (the larger values of 1/d), the experimental points normally drop below the curve of the preceding relationship and this is due to the fact that the value of a begins to increase significantly as the velocity drops off to a sufficiently small value

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[4] Eyring, H., Powell, R. E., Duffy, G. H. and Parlin, R. B., "The Stability of Detonation," Chem. Rev. 45, 69 (1949).

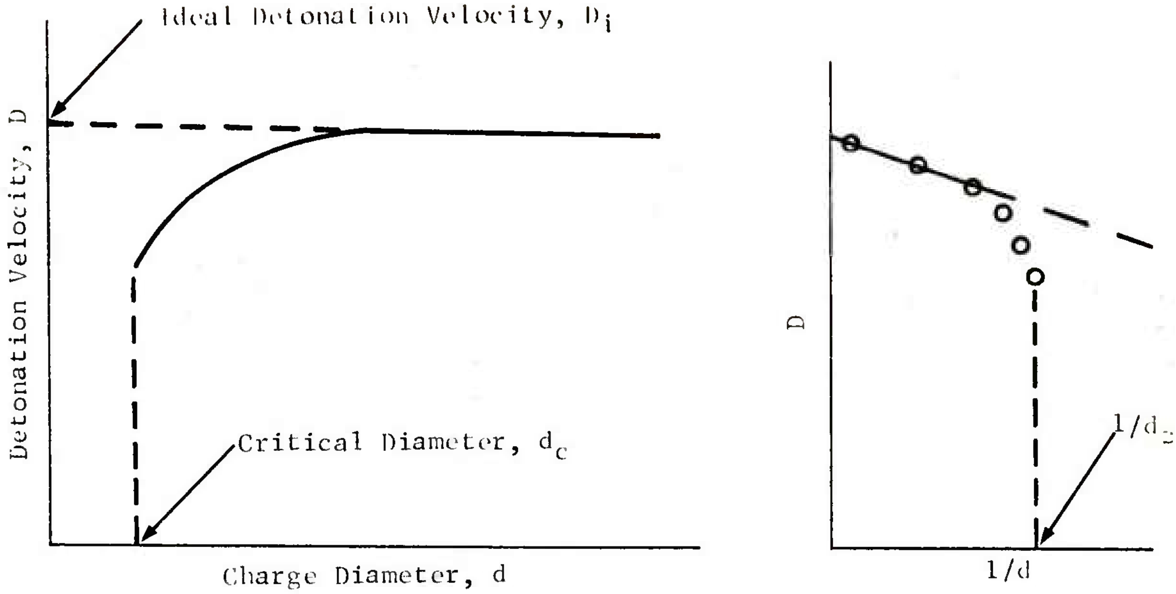

Figure 1. General Detonation Behavior of an Explosive.

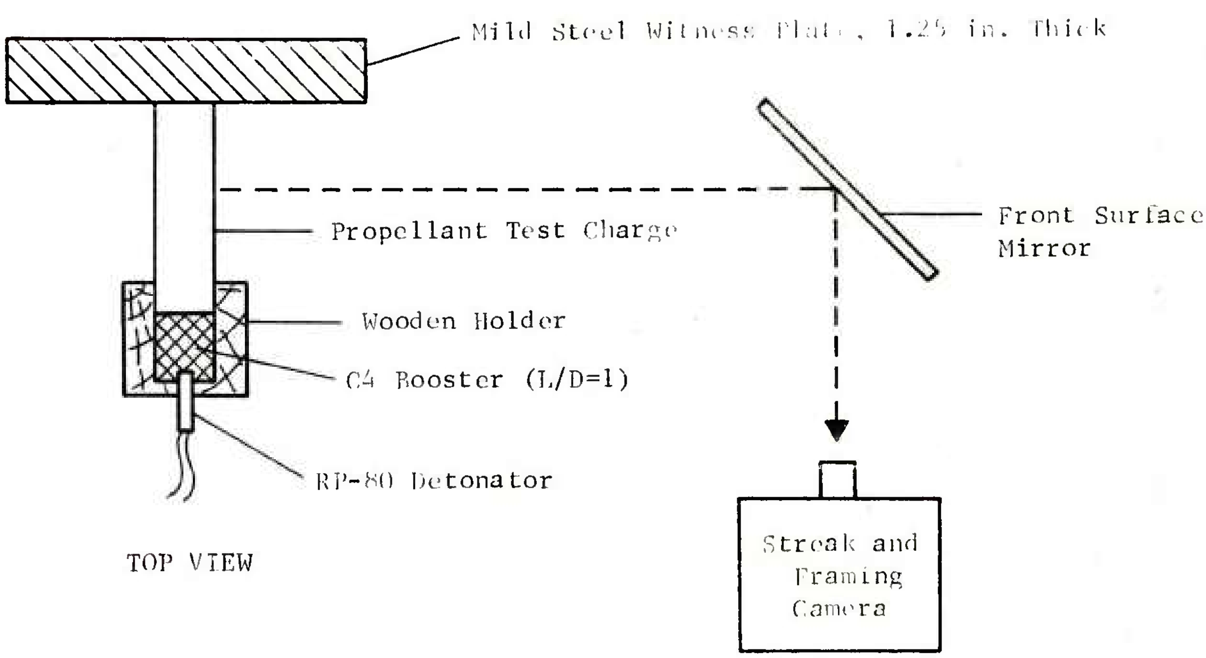

Figure 2. Experimental Setup for Photographing the Propagation of Detonation in the Propellant Test Charges.

(i.e., the detonation reaction rate decreases with a decrease in D). For charge diameters smaller than the critical diameter, the reaction rate is sufficiently small (with respect to the energy loss rate) that the reaction cannot propagate. The critical diameter of an explosive depends on a variety of factors including the reaction kinetics and the porosity content of the explosive charge.

2.2 Experimental Measurements

In the program, an attempt was made to obtain both the detonation velocity vs charge diameter relationship of the propellant and its critical diameter.

2.2.1 Test Charges

All of the studies in this report were conducted on LOVA-X1A propellant, which consists of small grained HMX explosive (75 wt%)* in a polyurethane binder (25 wt%). The test samples were provided by the U. S. ARRADCOM Ballistic Research Laboratory, and were manufactured by the Thiokol Corporation in Brigham City, Utah. The propellant is normally prepared in relatively small diameter grains by an extrusion process and in this case the grains generally contain very little porosity and have been said to have a density quite close to the theoretical density of 1.61 gm/cc (based on ρ_o (HMX) = 1.90 gm/cc, ρ_o (PU) = 1.107 gm/cc). For the detonation velocity and critical diameter measurements, however, relatively large diameter cylinders were used in some of the tests. Consequently, the propellant charges used in these measurements (except those with the smallest diameters) were prepared by casting the propellant in prefabricated molds.

Most of the tests samples arrived just before a meeting with the Contract Monitor. In order to quickly obtain some test results for this meeting, several initial charges were fired without x-ray examination, although their weight and dimensions were measured. A little later, most of the remaining charges were x-rayed and some density measurements were made. The samples were chalk white in color and consisted of cylindrical charges of various diameters, whose lengths were about 7 in. The exterior appearance of many of the samples was not exceptionally good (were rough and not smooth), and exhibited surface defects such as pock marks. The exterior appearance was generally poorer for the larger diameter charges, and this was also true of the interior quality as observed by x-ray. Table 1 summarizes the results of the x-ray and density measurements of the charges (the 0.25 and 0.375 in. diam. charges were prepared by extrusion, the others by casting).

The x-ray examination of the cast propellant charges showed that a large fraction of the charges had internal defects such as pores, cracks and density striations. The general appearance of the x-rayed interior of the charges was worst (more porosity) for the larger diameter charges, and improved as the charge diameter was decreased. A summary of the appearance of the charges x-rayed is as follows: 2.5 in. diam., 5 charges, all looked bad; 2.0 in. diam., 4 charges looked bad, 2 charges reasonably good; 1.5 in. diam., 5 charges, all looked bad; 1.0 in. diam., 5 charges, all looked bad; 0.5 in. diam., 6 charges, 3 looked fair, 3 looked good (but one was broke).

* 75% HMX: $\sim$65% fluid energy milled (FEM), with WMD $\simeq 4\mu$; $\sim$10% Class 5, with WMD $\simeq 15\mu$ (WMD = weight-mean diameter).

TABLE 1. Detonation Velocity Measurements of the Test Charges

Test Number	Charge Diam. (in.)	X-Ray Appearance	Charge Density (gm/cc)	Detonation Velocity (m/sec)
1	1.5	NA[1]	(1.60)[2]	8053
6	1.5	poor[3]	(1.61)	8105
12	1.5	poor	(1.53) 1.53	7872
2	1.0	NA	(1.65)	7897
5	1.0	NA	(1.66)	7841
11	1.0	poor	(1.56) 1.56	8211
3	0.5	NA	(1.59)	7724
4	0.5	NA	(1.64)	7846
7	0.5	good	(1.86)	8070
8	0.5	good	(1.91)	8102
9	0.5	fair	(1.60) 1.58	8006
10	0.5	fair	(1.55) 1.58	7900
15	0.375	fair-good	NA	7526
16	0.375	fair-good	NA	7328
13	0.25	fair-good	(1.58) 1.57	Failed
14	0.25	fair-good	(1.58) 1.58	Failed

[1]NA-Not available, fired before measurement

[2]Densities enclosed in parentheses were obtained using the weight and measured dimensions of the charge. The densities given without parentheses were obtained using immersion weighing.

[3]The descriptive words are with respect to the presence (and size) of internal defects (pores and cracks) within the charge; thus poor denotes many defects, and good denotes very few (and small).

An estimate of the average densities of the charges was made in the first eight tests by weighing the charges and measuring their dimensions with a steel rule (having 1/64 in. divisions). These values are given in parentheses in Table 1. The values obtained in this manner were not generally very accurate, due in part to the fact that the charges were not all completely uniform in diameter, but the values are indicative (charges 7 and 8 seem to be significantly in error). In later tests, the steel rule was replaced by calipers (the results of these measurements are also shown in parentheses), and in addition density measurements were made using a second method. This (more accurate) method consisted in weighing the charges in air and while they were immersed in water, using an Arbor electronic balance that had a sensitivity of 1 mgm and a precision of 0.5 mgm. The density values obtained by this method are also given in the table (without parentheses). This method had earlier been used in measuring the density of small cylinders (1.5 in. diam. x0.75 in. thick) of this same propellant on another program (to be discussed). In that case the measured density of the samples was found to be 1.605 gm/cc, which was in good agreement with the theoretical density of 1.61 gm/cc (the samples contained some very small defects. For the charges on the present program, however, the density was lower (as seen in the table) due to the presence of numerous internal defects, as just discussed (even the 0.25 in. diam. grains had defects). It may also be seen that the densities obtained using the caliper measurements of charge diameter were in good agreement with the densities obtained using the immersion weighing technique.

2.2.2 Detonation Velocity Measurements

Figure 2 shows the experimental setup used in the measurements. The cylindrical propellant test charges were initiated to detonation using an RP-80 detonator and Composition C4 booster (L/D = 1) train. The history of the detonation propagation in a charge was recorded by means of a high speed Beckman and Whitley framing and streak camera. Additional information regarding the intensity of detonation was obtained from a mild steel witness plate (1.25 in. thick) in contact with the test charge.

The detonation velocity was constant throughout most of the entire charge length for all of the charges, except for the 0.25 in. diam. charges-which failed to propagate detonation. Good streak and framing camera records were obtained of the events, and some typical pictures of the records are given in Fig. 3.* The detonation velocity measurements were made from the streak camera records, since streak records can conventionally be read more accurately than framing records (the uncertainty in reading the film was generally of the order of 1-2% in the velocity). To provide a scale for the distance coordinate as the detonation propagated horizontally along the charge (in the x direction), a static picture of the final setup of the charge with the booster and witness plate in place was taken, in which a ruler was placed beneath the charge. In addition, three or four copper wires (1 in. apart) were usually wrapped around the charge to provide more distinct fiducial marks for the propagation measurements. The y axis of the streak record represents the time coordinate and its scale is related to the camera speed. The detonation velocity at any horizontal distance in the charge is determined by the slope of the streak record at that particular location. The average detonation velocity between any two horizontal points in the charge is deter-

*Note how the light intensity decreases with decreasing charge diameter.

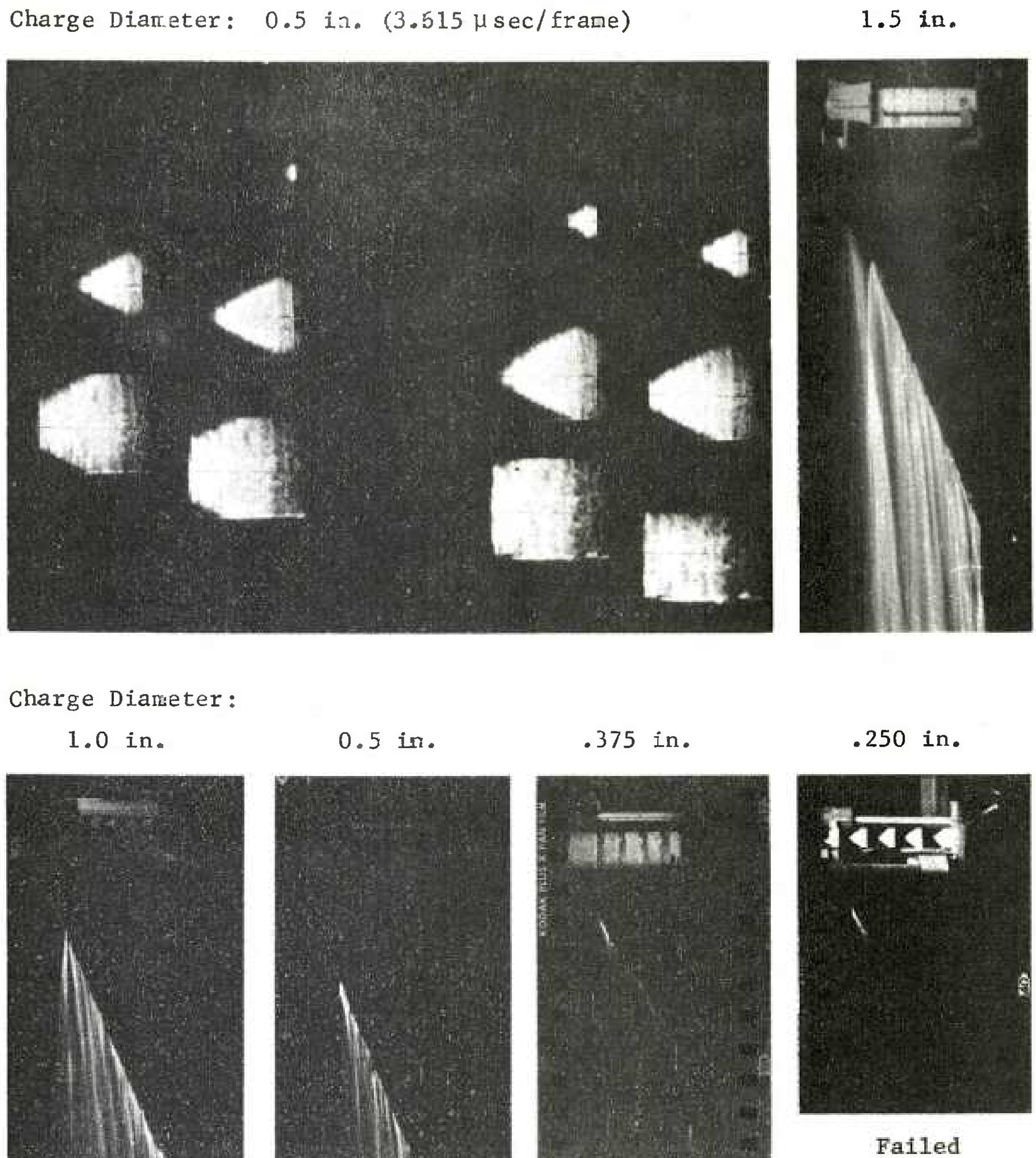

Figure 3. Typical Framing and Streak Camera Records of the Detonating Propellant.

mined by the average slope of the streak record between these two points. In practice this detonation velocity, D, is obtained directly from a knowledge of the time, t, that is required for the detonation to propagate the measured distance, x, i.e., $D = x/t$, where t is evaluated using a conversion factor that invloves camera speed.

Plate dents (in the witness plate) were also obtained in the tests. All of the charges that propagated detonation produced good sharp dents in the plate (the plate was not cut through.). In addition the back side of the plate was bulged for the 1 and 1.5 in. diam. charges, but not for the 0.5 or 0.375 diam. charges. In the case of the 0.25 in. diam. charges (which did not propagate detonation), only a light surface mark (no dent) was produced in the plate.

2.3 Experimental Results

The measured detonation velocities of the tested charges are summarized in Table 1. If the detonation velocities at each charge diameter are averaged, the velocities decrease with decreasing diameter, with the largest decrement occuring between the smaller (0.5 and 0.375 in.) charges, as is to be expected. The 0.375 in. diam. charges propagated detonation; whereas the 0.25 in. diam. charges did not propagate detonation. Thus the critical diameter of the bare (unconfined) propellant lies between these values.

On a more exact basis, however, the preceding averaging of the detonation velocities is only valid if all of the charges have the same density, which did not seem to be the case. In principle, the detonation velocity of the different charges should be normalized to the same charge density before they are averaged at each diameter. It is estimated that for pure HMX, a change in charge density of 0.1 gm/cc produces a proportional change in detonation velocity of about 330 m/sec, and this value should also be roughly applicable to the present propellant. However the general uncertainty in the charge density of most of the charges (those fired without the immersion weighing measurements) prevents the normalization with any reliability (the velocity changes from normalization are also generally small and within the experimental uncertainty in reading the streak records). Nevertheless, it is evident from the data given in the table that the detonation velocity of the propellant is relatively (but not completely) constant between a charge diameter of 1.5 and 0.5 in. decreases sharply as the diameter is reduced from 0.5 to 0.375 in. and fails to propagate at some diameter between 0.375 and 0.25 in. and below. This sharp decrease in velocity over a relatively small diameter change (at small diameters) is characteristic of many cast (high density) solid explosives and liquids. For most low density powdered explosives the velocity decrease is more gradual.[5]

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[5] Cook, M.A., The Science of High Explosives, Reinhold, N.Y., 1958, Chapt. 3,6.

2.3.1 Detonation Characteristics

It is possible to judiciously select data from the table (with or without normalization) and obtain an estimate of the detonation velocity vs charge diameter curve of the propellant. For example, Fig. 4 shows the curve that is obtained by using the directly averaged data at each diameter, but neglecting tests 7 and 8 of the 0.5 in. diam. charges. This approximate curve represents essentially the most simple averaging of the data, and would correspond roughly to that of the propellant at a charge density of about 1.58 gm/cc (neglect of the two tests is consistent with their (presumed) higher densities; the other data variations are assumed to be random). Other methods of averaging would produce (generally) small variations in the curve. The lower curve in Fig. 4 shows that the upper curve is consistent with Eq. (1) at the larger charge diameters, as discussed in section 2.1. The ideal velocity according to this plot is about 8100 m/sec, and using Eq. (1) gives an ideal reaction zone thickness of about 0.39 mm (small changes in the curve can change this value by a small factor). This value is of the same general magnitude as the reaction zone thickness of many cast explosives.[5,6] For example, 65/35 Composition B has a reaction zone thickness (by the same type of analysis[6]) of 0.16 mm, and its ideal velocity (8040 m/sec) is about the same as that of the LOVA-X1A propellant. The critical diameter of this explosive is about 0.16 in. It is of interest to note that the ratio of critical diameter to reaction zone thickness of Composition B (i.e., 0.16 in./0.16 mm), is about the same as for LOVA-X1A propellant (0.375 in./0.39 mm). Thus (in the same units), the critical diameter is about 25 a in these cases (a is the ideal reaction zone thickness). However this relationship may not always apply, since small degrees of porosity can in some cases have a strong effect on the critical diameter, while possibly having only a small effect on the reaction zone thickness. Nevertheless it offers food for thought in the development of new propellant compositions, since some of the detonation properties can be estimated for small changes in composition once the properties are known at a particular composition.

The preceding analysis showed that the ideal reaction zone thickness of LOVA-X1A propellant is larger than for Composition B, which implies that its reaction rate is slower. This seems reasonable since the LOVA-X1A propellant is more insensitive to shock and impact than Composition B (to be shown), and its critical diameter is larger. However, the reaction zone length at the critical diameter is larger than the ideal value (as discussed previously), and results in the experimental detonation velocity falling below the theoretical value (dashed line) in the lower figure in Fig. 4. The reaction zone length at the critical diameter can be estimated by substituting the average detonation velocity obtained for the 0.375 in. diam. charges (table 1) into Eq. 1. The resulting value is 0.79 mm, which is about double the ideal value. The ratio of critical diameter to the actual reaction zone thickness at the critical diameter is thus about 12.5. Further food for thought.

2.3.2 Effect of Charge Confinement

Some information regarding the effect of confinement on the critical

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[6] Johansson, C. H. and Persson, P.A., Detonics of High Explosives, Academic Press, N. Y., 1970, Chapt. 1.

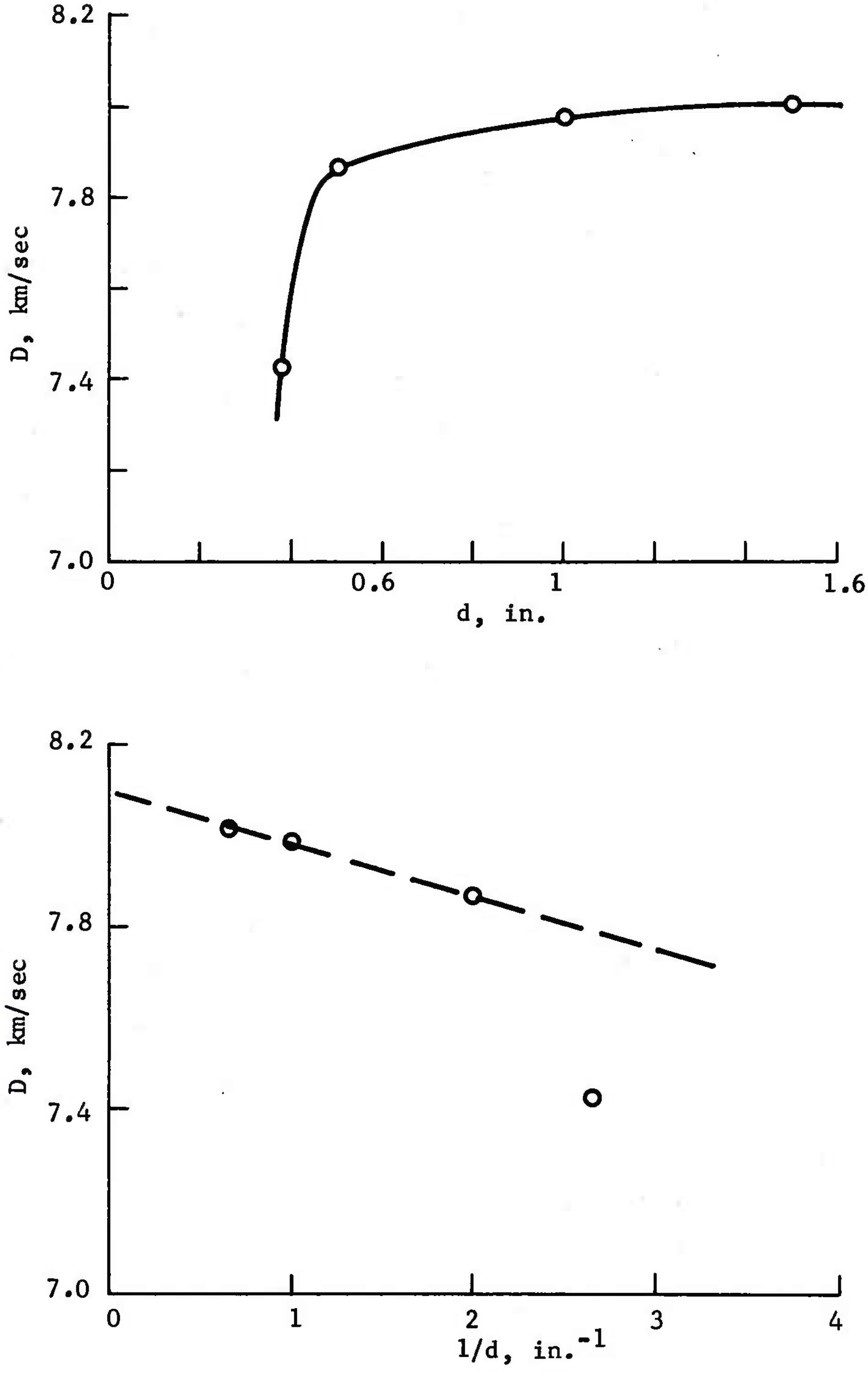

Figure 4. Experimental Detonation Velocity of the LOVA-X1A Propellant as a Function of Charge Diameter (approximate).

diameter of the LOVA-X1A propellant was obtained as a prelude to the shock sensitivity studies (discussed in the next section). It is known that enclosing an explosive in a casing will increase its nonideal detonation velocity, and decrease its critical diameter.[4-6] The question arose as to whether a 0.2 in. diam. charge of the propellant would propagate detonation if confined in a 1 in. diam. solid brass cylinder (with an axial hole for the charge). These are the dimensions of charge and confinement that are used in the NOL small scale gap shock sensitivity test apparatus that was being considered for use.[7]

Some preliminary detonation tests were subsequently conducted with a confined 0.25 in. diam. charge, since this size grains of the propellant were on hand. The diameter of the grains actually ranged from about 0.23 to 0.25 in. and was not constant, but rather slightly corrugated or tapered. The average diameter was about 0.245 in. (the same type of grains as used in tests 13, 14 of Table 1).

In the tests, individual extruded solid grains of the propellant were cemented (using a fast setting epoxy) in a 0.25 in. diam., 2 in. long hole bored in a 1 in. O.D. brass rod (Alloy 360, half hard free cutting) and initiated to detonation. The cylindrical donor explosive was 0.25 in. diam x 0.75 in. long, of hand-packed C4 explosive initiated by a #8 detonator. The ends of the propellant were flush with the ends of the brass acceptor tube. A mild steel witness plate was used to detect the presence of a propagating detonation in the propellant. The apparatus simulated the NOL small scale gap test apparatus, except that the hole containing the acceptor (test) charge was 0.05 in. larger.

Three similar tests were conducted, which resulted in one propagating detonation and two failures. For one of these failures the glue was dried overnight before firing the charge, and in the other cases the glue was allowed to dry for about two hours. The detonation produced a significant identation in the witness plate, but the failures gave only a surface mark outlining the brass tube (two slight concentric circles). Both the donor and acceptor tubes were blown into pieces. From the burn marks in the pieces of the two failure tests it could be seen that detonation was initiated in the propellant by the donor but did not prevail.

These results showed that the diameter of the confined propellant was marginal for propagating detonation and therefore was too small for use in the shock sensitivity tests (small difference in grain diameter may have caused the differences in the test results). The results also showed that the casing did not have a very large effect on the critical diameter of the propellant. Thus a 0.375 in. diam. bare charge always supported detonation; whereas a 0.245 in. heavily cased charge only supported it marginally. This suggest that the critical diameter of the bare charge is probably closer to 0.375 in. than to 0.245 in., since confinement should have some effect.

[7]Price, D. and Liddiard, T.P., "The Small Scale Gap Test: Calibration and Comparison with the Large Scale Gap Test," NOLTR 66-87, July 1966.

SECTION 3

SHOCK SENSITIVITY MEASUREMENTS

The preceding section showed that the critical diameter of the bare LOVA-X1A propellant is about 0.375 in. (it lies between 0.245 and 0.375 in.) and that the charge diameter must be critical or larger in order for detonation to propagate in the charge. However, in order for the propellant to undergo detonation, it must be suitably initiated. An important method of obtaining information regarding the potential detonation hazard of a particular explosive composition thus involves measuring the sensitivity of the material toward shock initiation to detonation. This is conventionally accomplished using the so-called card gap (or gap) test, and this test was used on the present program to measure the shock sensitivity of the LOVA-X1A propellant.

3.1 Outline of the Procedure

The test consists of passing the shock wave produced by the detonation of a standard donor explosive through a gap filled with an inert shock-attenuating material and into a standard sample of the test material.[7] The thickness of the gap material at which there is 50% probability of initiation of the test sample material to detonation (indicated by witness plate indentation) is a measure of the sensitivity of the material. A larger gap thickness indicates a more sensitive material since the pressure of the wave that causes the initiation is then lower.

There are a variety of general designs and sizes of apparatuses that have been used in gap test studies (e. g., Fig. 5, 6). The most important constraint is that the diameter of the test sample be greater than the critical diameter of the material. Generally speaking, however, it is usually desirable that the same apparatus be used to test all of the materials that are being compared so that essentially the only important variable on the results is the differences in the materials. This has lead to the standarization of certain designs of the test apparatus within a given organization for conducting the tests, but not all organizations use the same design.[7] Different designs for example may (1) employ different donor explosives, (2) use a different diameter and length of the donor explosive and of the test sample, (3) confine the test sample in a different manner (including using a bare charge), and (4) employ different gap materials (both metals and plastics have been used).

An evaluation of the relative shock sensitivity of a new material (e.g., LOVA-X1A) with the sensitivity of other propellants and explosives is made by comparing the card gap thickness of the new material with those of other materials whose general relative sensitivities are known in terms of field experience and use over the years. For a more quantitative comparison it is possible to make an estimate of the shock pressure of the initiating shock wave.

3.2 Experimental Measurements

In the measurements, it was desirable to keep the diameter of the test charges small because of cost. In addition, the detonation studies (discussed before) showed that the larger diameter charges always contained numerous internal

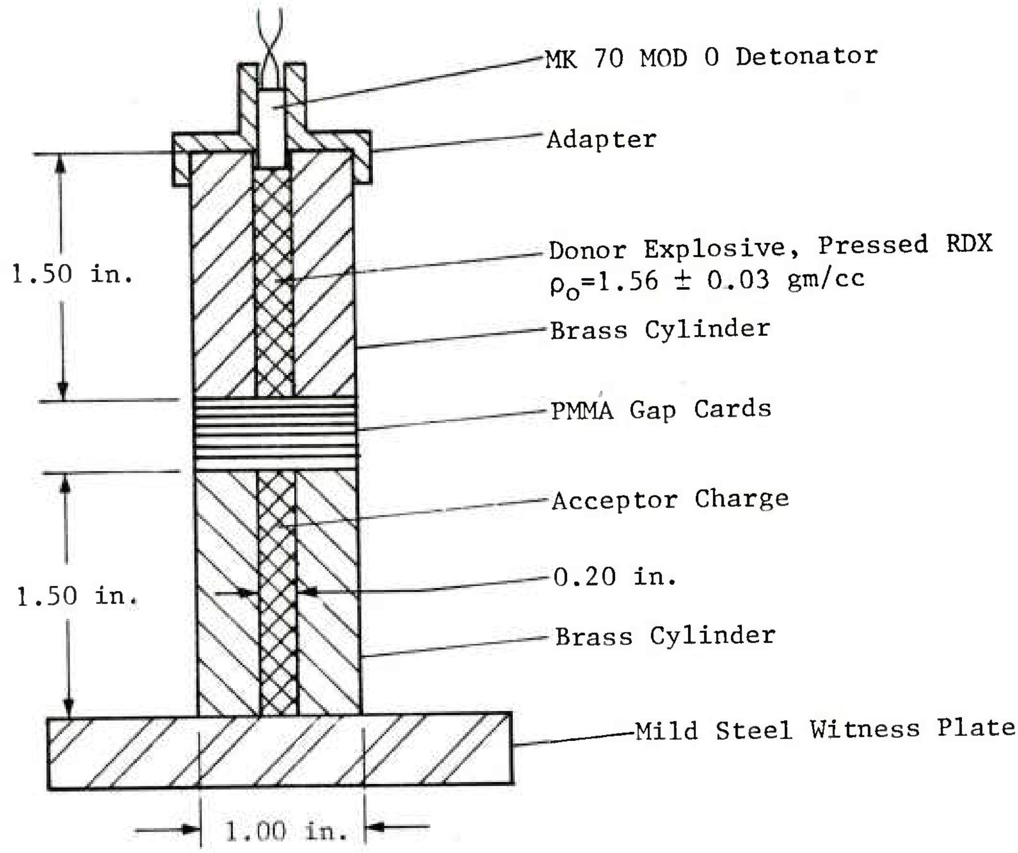

Figure 5. The NOL Small Scale Gap Test (SSGT) Apparatus.

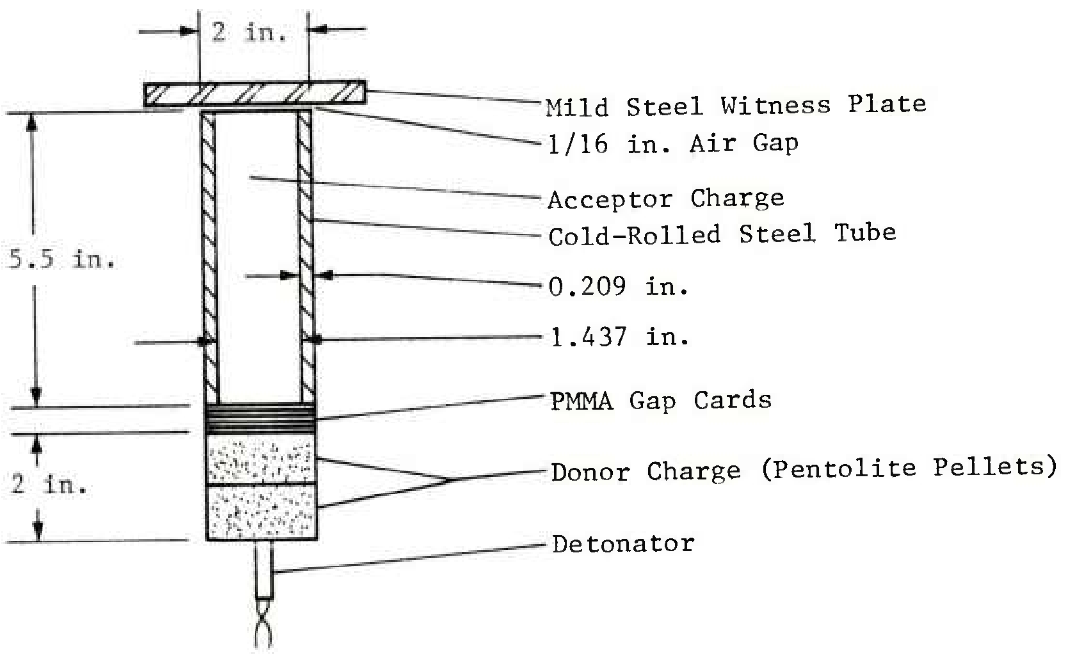

Figure 6. The NOL Large Scale Gap Test (LSGT) Apparatus.

defects, and these are known to affect (increase) the shock sensitivity of an explosive. For this reason, the small scale gap test (SSGT) apparatus developed at the Naval Ordnance Laboratory (NOL, now called the Naval Surface Weapons Center) was initially considered for use (shown in Fig. 5). A significant amount of test data on a variety of explosives has been accumulated over the years using this apparatus.[8] In this apparatus, the donor and acceptor charges have a diameter of 0.2 in., and are each confined in a 1.5 in. long, 1 in. OD brass tube. The donor explosive is RDX pressed to a density of about 1.56 gm/cc.

Because the critical diameter of the bare LOVA-X1A propellant was larger than 0.2 in., the question arose as to whether detonation would propagate in the heavily confined propellant as used in the test. The preliminary experiments described earlier (section 2.3.2) showed that detonation was marginal for even a 0.25 in. diam. charge, and therefore a larger diameter was required. Consequently, in order to satisfactorily conduct the tests and also use the previous results of the SSGT apparatus for comparison, a slightly scaled-up version of the apparatus was used (further discussion is given later). This apparatus used a diameter of 0.375 in. for both the donor and acceptor charges, since it was known that detonation would always propagate in the bare (and hence then also in the confined) test propellant, if it was suitably initiated. The scale factor was consequently 0.375/0.2 = 1.875, and all dimensions of the SSGT apparatus were enlarged by this factor in the design of the gap test apparatus used for the tests (shown in Fig. 7). Actually the scale-up of all dimensions of the apparatus was not really necessary, since some of the dimensions have no effect as long as they are within certain bounds. Thus the length of the test charge is of little significance, and need only be long enough to allow the reaction induced by the entering shock wave (from the gap material) to either build up to a propagating detonation, or fade (die-out) before it reaches the witness plate. This usually occurs within several charge diameters at the most. The length of the donor charge is likewise of little consequence, since it is only about the last charge diameter or so of length that contributes significantly to the pressure pulse that is imparted to the gap material. However, several charge diameters of propagation are desirable to insure a steady pressure profile before impact of the wave with the gap material. The casing thickness ceases to have much effect as the degree of confinement is increased sufficiently. The degree of confinement for the SSGT apparatus is essentially infinite as far as detonation effects are concerned[4], and this same degree is maintained in the scaled-up version. However a smaller degree (smaller wall thickness) would have little effect on the results. Nevertheless, all the dimensions of the SSGT aparatus were scaled-up in the design of the apparatus used for the tests.

A separate apparatus was required for each test, since they were destroyed by the detonation of the charges. The cylinders used for confining the charges were prepared by boring a 0.375 in. diam. hole in a 1.875 in. diam. brass rod (Alloy 360, half hard free cutting), and cutting the rod into 2.8 in. long sections. The test charge sections were prepared by extruding the propellant directly into the hole of the section, which provided a firm bond with the metal (performed by Thiokol Corp.). The propellant on both ends of the

[8]Ayres, J. N., Montesi, L. J. and Bauer, R. J., "Small Scale Gap Test Data Compilation: 1959-1972, Unclassified Explosives," NOLTR 73-132, Oct. 1973 (AD-773-743).

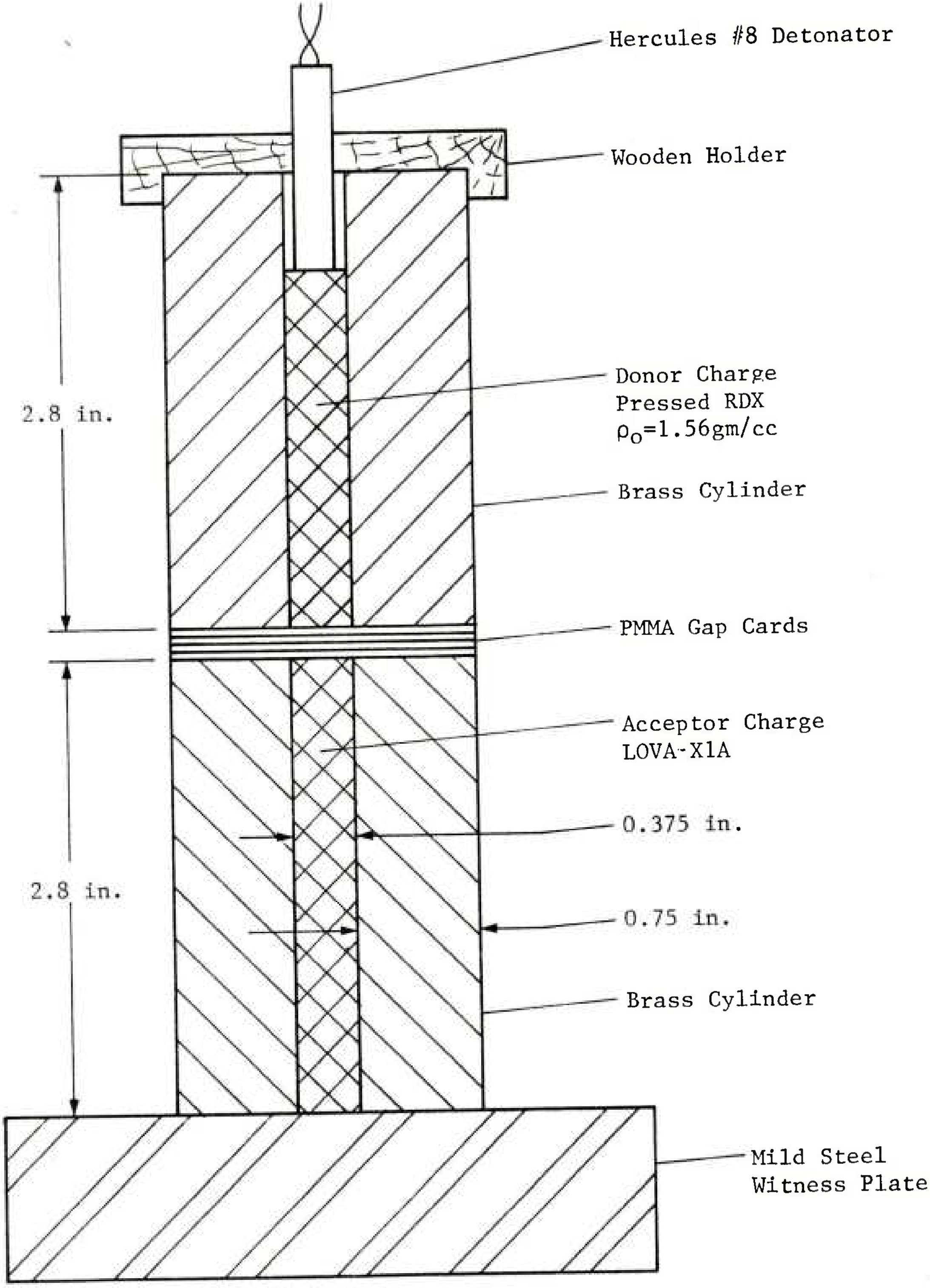

Figure 7. Scaled-up SSGT Apparatus That Was Used to Determine the Shock Sensitivity of the LOVA X1A-Propellant.

section was smoothed flush with the metal. The donor charge sections were prepared by incrementally pressing RDX powder into the hole in the metal sections at a pressure of about 8000 psi, to obtain the desired density of about 1.56 gm/cc (the average density of the 21 prepared charges was 1.56, with a standard deviation of 0.014 gm/cc). The explosive was smoothed flush with the metal on the end adjacent to the gap material. The donor explosive was initiated to detonation by a #8 detonator (Hercules) mounted flush on the top of the explosive.

The gap material was square sheets of Plexiglas (PMMA), approximately 1.875 in. on a side, cut from a larger 0.02 in. thick sheet. However it was found that there was some fluctuation in thickness between the individual cards, the gap thickness used in the various tests was obtained by measuring the total card thickness (at a corner) with a micrometer after the apparatus was assembled and ready for firing. The individual card thicknesses were also measured. The total measured gap thickness was usually (but not always) slightly greater than the sum of the individual cards (by about 0.001 - 0.005 in.).

3.3 Experimental Results

The results of the gap test measurements are shown in Table 2, and summarized in Fig. 8. At the smaller gap thicknesses the tests all resulted in the detonation of the propellant (were Goes), and at the larger gap thicknesses the tests resulted in no detonation of the propellant (were No-Goes). However, over a region of about 2 mm of gap thickness, centered at 3.5 mm thickness, the tests gave both Goes and No Goes with roughly equal probability. The relatively small number of tests indicates that it is not significant to apply Bruceton or other common sensitivity statistics to the results.[9] However, drawing a line between the gap thickness extremes of the overlap region (Fig. 8) gives a value of 3.505 mm as a measure of the gap thickness for 50% probability of initiation of the propellant to detonation. This same value is also obtained if all of the gap thickness in the overlap region are averaged, and the standard deviation in this region is then 0.66 mm. Thus to the present degree of accuracy, the average gap thickness for 50% probability of initiating the LOVA-X1A propellant to detonation in the scaled-up version of the SSGT apparatus (Fig. 7) is about 3.505 mm of Plexiglas.

3.3.1 Discussion

The shock initiation of an explosive in a card gap test is a relatively complex process, that is only partially understood. The magnitude of the initiating shock pressure is the factor that has generally been considered of most importance in past discussions of the test. For the moment, assume this to be true. The initiating shock pressure, P_i that is transmitted into the propellant is determined by the incident shock pressure, P_g, in the Plexiglas gap material (at the Plexiglas-propellant interface) and the shock Hugoniot of the propellant and gap material. The shock pressure, P_g, in the Plexiglas

[9] Martin, J. W. and Saunders, J., "Bruceton Tests: Results of a Computer Study on Small Sample Accuracy," Preprints, International Conference on Sensitivity and Hazards of Explosives, ERDE, London, Oct. 1963.

TABLE 2. Results of the Shock Sensitivity Tests.

GAP THICKNESS (mm)			
GO	NO-GO	GO	NO-GO
0		3.48	3.48
1.83		3.56	3.56
3.10		3.58	3.58
3.12			3.63
3.30			3.68
3.33			3.71
3.33			4.11
3.43	3.43		5.16
3.45			

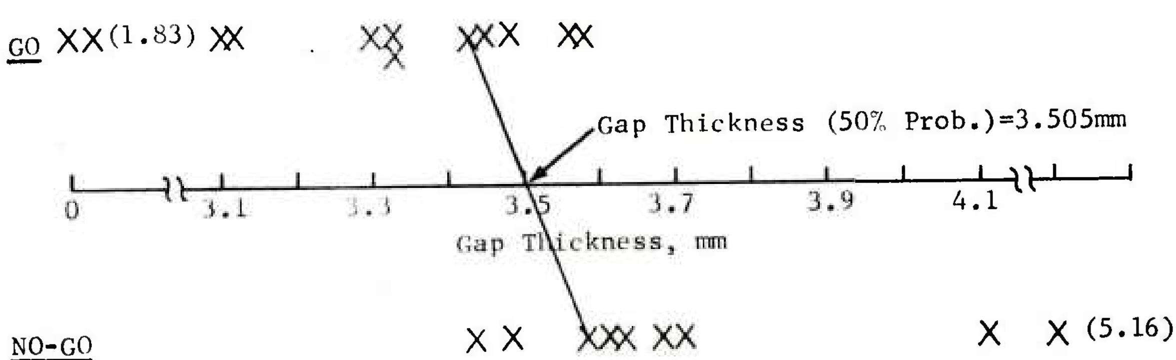

Figure 8. Summary of the Shock Sensitivity Tests.

in the SSGT apparatus has been measured as a function of gap thickness, y, and is given by[7]

$$P_g = 309/y^{1.4}, \qquad y \geq 2 \text{ mm} \qquad (2a)$$

$$P_g = 216-49.456y, \qquad y \leq 2 \text{ mm} \qquad (2b)$$

where P_g is in kbar and y in mm (the second equation is an approximation). The 50% probability initiating gap thickness of the propellant in the scaled-up gap test apparatus (Fig. 7) was 3.505 mm. This would correspond to a thickness of 3.505/1.875 = 1.869 mm in the SSGT apparatus. From Eq. (2b), this gives a pressure of 123.6 kbar in the Plexiglas (measurements in ref. 7 on a model of the SSGT apparatus scaled up by a factor of five showed that scaling the apparatus gives valid scaled measurements).

As just noted, this incident pressure (P_g) is not the true initiating pressure (P_i) transmitted into the propellant (which for most materials is about 10-30% larger). The incident pressure is, however, the pressure that is normally used in discussions of the shock sensitivity of materials as determined by a card gap test. This is partially because the shock Hugoniot of most explosives is unknown, and in those cases P_i cannot be calculated (P_g is a measured quantity, whereas P_i must be calculated). However, it has been shown[10] using those explosives for which the shock Hugoniot is known, that the incident gap pressure generally orders the test explosives for shock sensitivity in the same way as does the initiating pressure. Thus the shock sensitivity of the LOVA-X1A propellant can be compared with that of other materials by comparing the value of P_g of the propellant with the P_g of the other materials.

3.3.2 Comparison of Shock Sensitivities

Table 3 (taken from ref. 7) shows values of P_g for several explosives at various charge densities, as obtained by the SSGT apparatus. The required incident pressure of the LOVA-X1A propellant (123.6 kbar) is very much larger than the values given for the conventional explosives (several tens of kbar or less), which means that the propellant is very insensitive to shock initiation compared to the explosives. The table illustrates that the shock sensitivity of a material is greater for a lower density charge (more charge porosity), and decreases significantly as the charge density is increased. Thus, for the most valid comparison, the preceding comparison should be made

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[10] Price, D., Clairmont, A. R. and Erkman, J. O.; "The NOL Large Scale Gap Test, III. Compilation of Unclassified Data and Supplementary Information for Interpretation of Results," NOLTR 74-40, March 1974.

TABLE 3. Experimental Critical Incident Shock Pressures Obtained in Card Gap Tests (from ref. 7).

COMPARISON OF LSGT AND SSGT RESULTS AT SAME % TMD****

Material	ρ_o	% TMD	50% Pressure P_g (kbar) LSGT	50% Pressure P_g (kbar) SSGT
NQ (LBD) X547	0.56	31.2	[15.2]	-
	0.90	50.3	18.5	22.5**
	1.20	67.4	41.0	55.7*
	1.27	71.5	46.8*	77.5
DATB X331	1.21	65.8	26.5	30.2**
	1.23	67.0	26.9*	30.7
	1.44	78.1	30.5	37.0*
	1.70	92.5	37.5	47.4
TNT X412	1.35	81.8	13.2*	17.1
	1.42	85.7	14.5	18.0*
	1.45	87.4	15.2*	18.5
	1.49	90.3	16.5	20.3*
	1.55	93.6	18.4*	22.2
	1.60	96.9	20.8	27.0*
	1.64	98.9	22.6	32.5*
TATB	1.82	93.9	58.8	(101.7)***

Material	ρ_o	% TMD	50% Pressure P_g (kbar) LSGT	50% Pressure P_g (kbar) SSGT
Tetryl X412	1.43	82.4	8.3	9.7*
	1.49	86.0	8.9	10.6*
	1.64	94.9	12.5	16.1*
CH-6 X445	1.45	81.3	7.3	9.6**
	1.51	84.9	7.4*	10.2
	1.57	88.2	7.7	11.2*
	1.60	90.0	8.1*	12.1
	1.64	92.1	8.6*	14.0
	1.68	94.4	9.4*	17.6
	1.70	95.5	9.9	19.7*
RDX X189	1.53	85.0	6.5	9.3**
	1.64	91.8	7.0	11.5*
EPM-2	1.72	91.7	13.1	15.5
Comp C3	1.61	-	20.2	37.6

* Interpolated
** Extrapolated
*** Nominal value
**** TMD - Theoretical Mean Density

with an explosive in its cast (essentially voidless) form.

The shock sensitivity of relatively insensitive propellants cannot usually be determined with the SSGT apparatus because the critical diameter of insensitive propellants is generally larger than the charge diameter of the apparatus. However, some information on propellants is available from the large scale gap test (LSGT) apparatus of NOL (Fig. 6). The apparatus has a test charge diameter of 1.437 in., and the charge is confined in a 0.21 in. thick steel pipe. The donor charge is unconfined, and has a length and diameter of 2 in. Table 3 shows the incident pressures that have been obtained for various explosives with the LSGT apparatus in comparison with the SSGT apparatus. At the smaller charge densities the values are approximately the same, although those obtained with the LSGT apparatus are always a little smaller than those from the SSGT apparatus. As the charge density is increased, however, the difference between the incident pressure values obtained with the two apparatuses appears to increase.

Table 4 summarizes the critical incident pressures that have been obtained on various explosives and propellants in the LSGT apparatus (taken from ref. 10 11). The data for TNT and Composition B illustrate that the shock sensitivity of a cast material is much less than that for the pressed material at the same charge density. This is because cast materials usually contain few voids, and what voids there are, are largely unconnected so that the charges are impermeable. Cast TNT is generally considered to be one of the most (or the most) insensitive materials used in ordnance applications.

Table 4 also summarizes the easily available (non-proprietory) sensitivity data on propellants. The measured pressures on voidless double base propellants range from 47-138 kbar, and depend on various factors. The sensitivity increases with increased nitroglycerin content, and decreasing content of the other (non-explosive) components. The critical diameter of conventional nonporous composite propellant (based on ammonium perchlorate) is much larger than the charge diameter in the LSGT apparatus, so that detonation cannot be initiated in the test. However, grinding the propellant and pressing it into charges with about 16% or more porosity content allows detonation to propagate[12], and in this condition the propellant can be initiated at very low pressures (7-11 kbar). This is likewise true for single base propellants. Including a high explosive as one of the components in a composite propellant reduces the critical diameter significantly, and also the sensitivity of the propellant. It should also be mentioned that increasing the ambient temperature of a propellant generally increases its shock sensitivity, and can also reduce its critical diameter.[10,13] The initiation and propagation behavior can become more complex in some cases if the temperature (especially very low temperatures) has a significant effect on the mechanical properties of the material. Also, long storage periods often increase the sensitivity of explosive materials.

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[11] Price, D. and Jaffe, I., "Large Scale Gap Test: Interpretation of Results for Propellants," ARS Journal 31, 595 (1961).

[12] Salzman, P. K., Irwin, O. R. and Andersen, W. H., "Theoretical Detonation Characteristics of Solid Composite Propellants," AIAA Journal 3, 2230 (1965).

[13] Amster, A. B., Noonan, E. C. and Bryan, G. J., "Solid Propellant Detonability," ARS Journal 30, 960 (1960).

From Tables 3 and 4 and the preceding discussion it can be seen that the shock sensitivity of the LOVA-X1A propellant, as determined by the card gap test, is significantly lower than almost all of the cast explosives and propellants that are used in real ordnance applications. Some additional data on propellants is given in ref. 14.

3.3.3 Other Considerations

As noted before, the shock pressure is the factor that has been considered to be of principal importance in most previous discussions of the gap test. This was believed to result from a steep pressure-time profile, such that the pressure amplitude dominates the initiation process.[10] However it is known that the pressure duration is also a factor in initiation, especially at the critical (50%) pressure level. Unfortunately the shock duration is not a clearly defined quantity in the gap test, and in fact it apparently varies with gap thickness and is therefore not constant. The pressure decay in the gap material is a complex process since it can be two dimensional in character (i.e., both a lateral and rear rarefaction may be involved in the pressure decay).

The difference between the test results obtained with the SSGT and the LSGT apparatus (table 3) was probably due to differences in their shock durations. Unfortunately the large differences between the designs of these two test apparatuses makes it difficult to estimate these durations. However, from the preceding considerations it can be seen that the scaling of a gap test (as was done on this program) is not necessarily always a simple matter. Thus, although the peak pressure can be determined directly in a scaled-up version of the test, the time duration of the pressure loading simultaneously increases (by the scale factor), which can complicate the interpretation of the results. Nevertheless, since the available results indicate that the pressure is of dominant importance in the gap tests, the comparisons given of the relative shock sensitivity of the LOVA-X1A propellant with various other propellants and explosives should be quite valid. Further information along these lines is given in the next section.

In closing this section, it is of interest to estimate the peak shock pressure that is transmitted from the gap material into the LOVA-X1A propellant. This initiating pressure, P_i, is determined by the incident shock pressure in the gap material, P_g (just discussed) and the shock Hugoniot of the gap material and propellant. Figure 9 shows the shock Hugoniot of the Plexiglas gap material (from ref. 10) and the assumed Hugoniot of the propellant (discussed later). The incident pressure of the Plexiglas at the propellant interface is 123.6 kbar (discussed before). Application of the standard reflection technique then gives a peak shock pressure of 145.3 kbar that is transmitted into the propellant and initiates the detonation reaction. This pressure is about 18% larger than that in the gap material. Some further related discussion is given in the next section.

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[14] Coleburn, N. L., "Sensitivity of Composite and Double Base Propellants to Shock Waves," AIAA Journal 4, 521 (1966).

TABLE 4. Critical Incident Shock Pressures Obtained in the LSGT Apparatus

Material	Density (gm/cc)	P_g (kbar)	Comment		
TNT	1.58 -1.64	20-26	Pressed Charge		
TNT	1.56 -1.62	44-88	Cast Charge		
Comp. B (60/40)	1.66	14	Pressed		
Comp. B (60/40)	1.69 -1.71	20-44	Cast		
Nitroguanidine	1.51 -1.64	69-93	Pressed		
Nitrocellulose	1.45 (92%TMD)	20	Pressed, 12.6% N		
Double Base Propellant		Composition →	NC	NG	Other
ARP	1.61	86	46.1%	39.1%	14.8%
JPN	1.62	70	51.4	42.9	5.7
AHH	1.60	90	54.6	32.1	13.3
OIO	1.55	118	59.1	25.2	15.7
OGK	1.53	138	57.3	24.3	18.4
Other	nonporous	47-80			
Composite Propellant		Based on Ammonium Perchlorate			
Conventional	nonporous	No Go	$d_c^* > d_o^{**}$ (d_c is several ft)		
Shreaded	highly porous	7-11			
Plus 18% explosive	nonporous	58-69			

* d_c = Critical diameter of the propellant, ** d_o = Charge Diameter in the LSGT apparatus

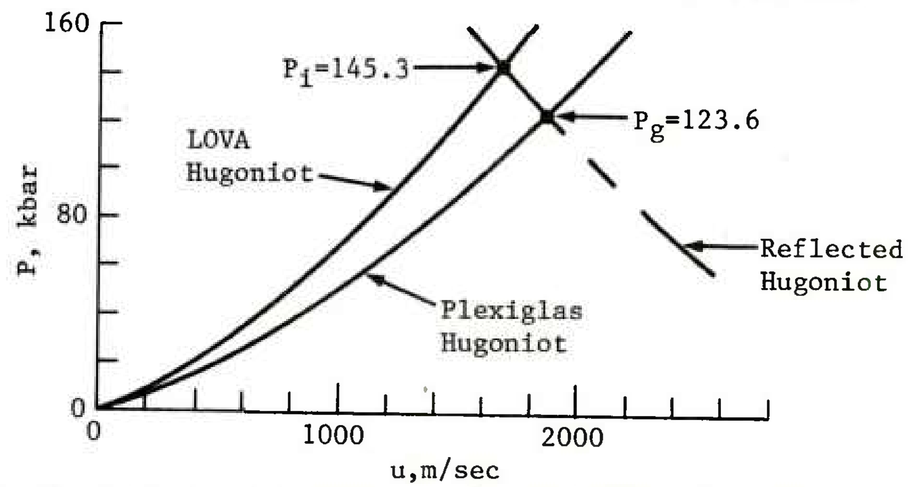

Figure 9. Shock Hugoniot Calculation of the Shock Initiating Pressure of LOVA-X1A in the Gap Test.

SECTION 4

PROJECTILE IMPACT SENSITIVITY

Shock Hydrodynamics has recently conducted studies of the sensitivity of the LOVA-X1A propellant (and also other propellants) to projectile impact ignition on a program with the Army Research Office. Some of the results of that investigation are of direct importance to this program, and will therefore be summarized here and discussed. Details of the studies are available in the original papers.[15]

4.1 Experimental Measurements and Results

The tests[15] consisted of impacting small cylinders (1.5 in. diam. x 0.75 in. thick) of the bulk, nonporous propellant with flat-ended brass projectiles of different diameters (.22, .257 and .50 caliber) fired from guns at various velocities, and observing the impact reaction by an open shutter camera, photocell, post inspection, and weighing of the propellant fragments.

The general behavior of the LOVA-X1A propellant to impact is shown in Fig. 10. The critical (minimum) impact velocity required to produce a sustained reaction in a sample decreased with increasing projectile diameter. This means that the propellant is more sensitive when struck by a larger diameter projectile. Below this critical velocity only breakup of the sample occurred (near the critical velocity some minor deflagration and decomposition occurs, but does not spread. This reaction showed up as sparks and flashes on the sensors). The nature of the induced reaction depended strongly on projectile diameter. At the smaller diameters, the impact induced detonation in the sample at the critical (and also at higher) impact velocities. A very high impact velocity was required. However, at the large (0.5 in) diameter, the critical velocity induced a sustained burning (rather than detonation) of the sample, and the initial intensity of the burning increased with increasing velocity. At a sufficiently high velocity and above, the impact then again induced a detonation in the propellant.

4.1.1 Impact Ignition Model

A model was postulated to explain the preceding results, and it is useful to summarize it here. The passage of the impact-induced shock wave in the propellant was assumed to initiate an exothermic ignition reaction at hot spots formed by the interaction of the shock wave with pores or other defects initially present in the unshocked material. The ignition incurs a small time delay that decreases with increased pressure. This causes the critical (minimum) impact velocity for ignition to decrease with increasing projectile diameter. After ignition, reaction and pressure buildup occur. It was postulated that the concentration of effective (ignited) hot spot sites controls the buildup rate, and that the concentration of effective sites increases

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[15] Andersen, W. H. and Louie, N. A., "Projectile Impact Ignition Characteristics of Propellants. I. Deflagrating Composite Explosive," Comb. Sci. and Tech. 20, 153 (1979).

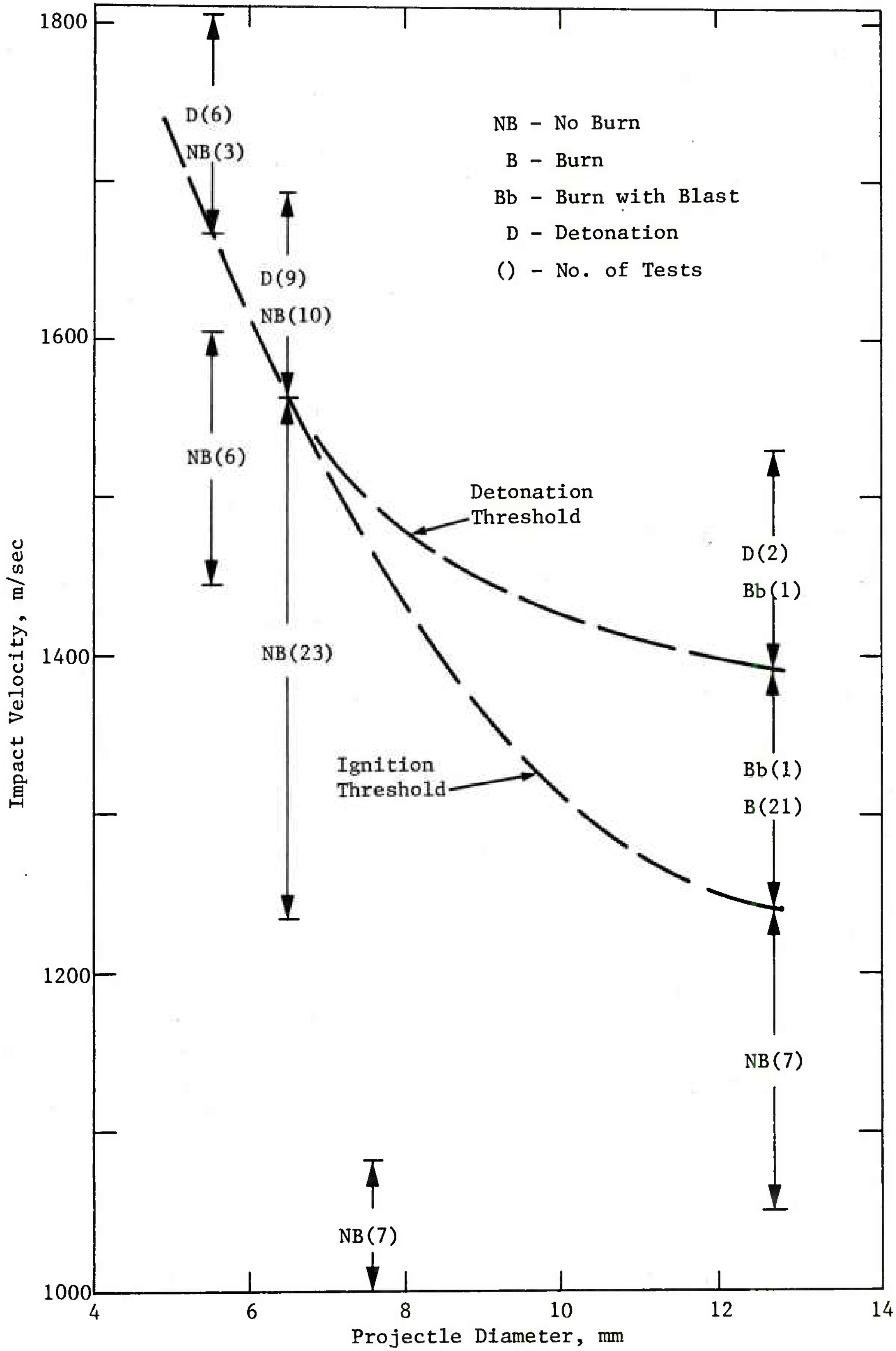

Figure 10. Impact Ignition Behavior of the LOVA-X1A Propellant.

significantly with increased pressure.[16] The general impact behavior of a propellant with specified composition (decomposition kinetics) and void concentration then depends in part on the pressure level required to produce the ignition reaction. A large concentration of ignition sites leads to rapid pressure buildup and detonation of the material. However, the reaction rate for a low concentration of sites is relatively small, which allows time for rarefaction loss and quenching to prevent the buildup. In this case only some manner of deflagration occurs (sample thickness can be of special importance here).

For the LOVA-X1A propellant, the porosity content was very small, and the effective thermal decomposition (energy release) rate relatively slow. Consequently, at small projectile diameters a very large impact velocity was required to initiate the propellant (essentially the same velocity as for a homogeneous nonporous propellant), since the concentration of effective ignition sites was then very large because of the high pressure. However, at the large projectile diameter the critical velocity was significantly smaller. The impact ignition in this case resulted in a deflagration since the lower reaction rate caused by the small concentration of ignition sites allowed rarefaction loss to prevent reaction buildup. A higher impact velocity (at the same diameter) increased the concentration of sites, which increased the intensity of the deflagration. Finally, at a sufficiently large impact velocity, detonation was produced here also as the result of a sufficiently high concentration of ignition sites.

4.2 Comparision with Other Materials

For the present purposes, the sensitivity of the impacted propellant to detonation is of prime interest. Figure 10 (also Table 5, discussed later) shows the threshold values of the impact velocity required to induce a detonation in the propellant. However these threshold values are probably a little lower than the true V_{50} necessary for initiating the detonation, since not enough tests were conducted to establish (statistically) the true V_{50} curve (V_{50} is the critical impact velocity required for 50% probability of initiating the detonation reaction). The averaged values given in Table 5 are believed to be a closer approximation to the true V_{50} values. Figure 11 shows the experimental critical impact velocities for the projectile impact initiation to detonation of several explosives (data taken from studies summarized in ref. 17, 18). The averaged values

[16] Walker, F. E. and Wasley, R.J., "A General Model for the Shock Initiation of Explosives," Propellants and Explosives 1, 73 (1976).

[17] Weiss, M. L. and Litchfield, E. L., "Projectile Impact Initiation of Condensed Explosives," Report 6986, Bureau of Mines, Pittsburgh, 1967.

[18] Price, D. and Jaffe, I., "Safety Information from Propellant Sensitivity Studies," AIAA Journal 1, 389 (1963).

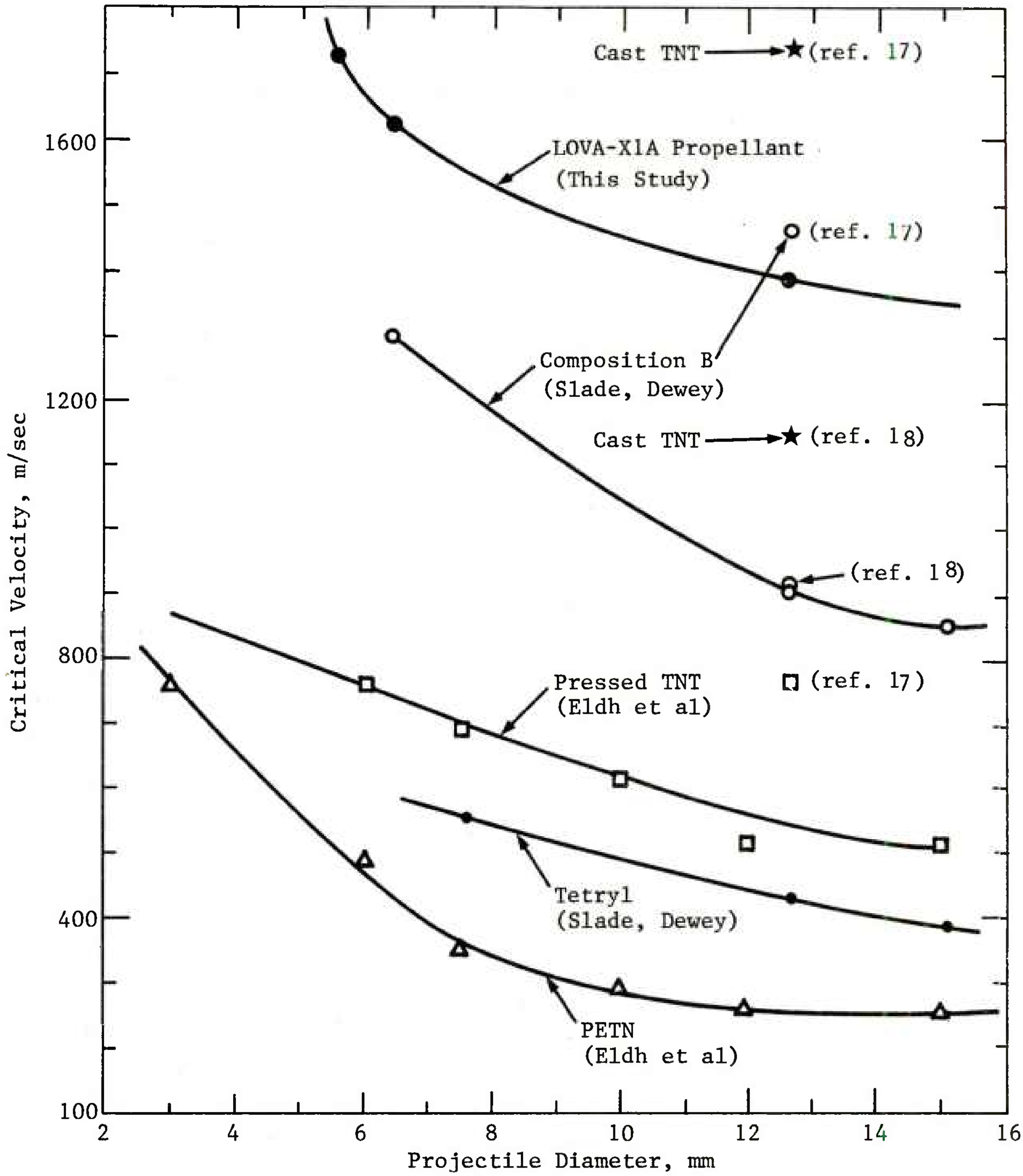

Figure 11. Critical Impact Velocity Versus Projectile Diameter for Various Explosives (data from ref. 17, 18).

of the LOVA-X1A propellant are included for comparison. The impact velocity necessary to induce detonation in the LOVA-X1A propellant is much higher than for ordinary pressed explosives such as TNT and tetryl. The LOVA-X1A propellant is therefore much less sensitive to impact initiation than pressed explosives. In the case of the more insensitive cast explosives such as TNT and Composition B the situation is less clear, since there is a considerable difference in the results that were obtained for these explosives by different investigators. This agrees with a statement in ref. 10 that the shock sensitivity of cast explosives (as measured by the LSGT apparatus) is less reproducible than pressed explosives (see Table 4), and can depend on a variety of factors such as charge composition, density and grain size. The critical impact velocities that have been obtained for these cast explosives using a .50-caliber, flat-nosed brass cylinder encompass a wide range and are both higher and lower than the value obtained for the LOVA-X1A propellant. On the average it appears that the propellant is less sensitive to impact than Composition B, and roughly of the same sensitivity as cast TNT. The ignition (combustion) curve in Fig. 10 possibly results from the short length (0.75 in.) of the propellant samples used in the impact tests, i. e., the sample length may not have been long enough to allow detonation to build up after the impact ignition. If that is the case, then the ignition curve in Fig. 10 represents the true impact detonation threshold for a sufficiently large propellant sample. However, this would not change the preceding conclusions on the basis of the available data.

4.2.1 Single, Double and Triple Base Propellant

In the preceding ARO investigation, experimental projectile impact tests were also conducted on a typical single, double and triple base propellant[19] (often called homogeneous or colloidal propellants); the results are shown in Fig. 12. A comparison of these results with those in Fig. 10 shows that the collodial propellants exhibited the same general impact behavior as the LOVA-X1A propellant (except that the test data are not as complete). The magnitude of the critical impact velocity that is necessary to induce detonation in the colloidal propellants is a little higher (at all projectile diameters) than for the LOVA-X1A propellant; and the critical velocity necessary to induce burning at the largest diameter is lower. However, the small difference in detonation sensitivity would not likely be of any significance in the use of the materials. The available projectile impact data indicate that the reaction of the propellant grains in a cased munition results from thermal mechanisms rather than the direct shock initiation of the material. The induced reaction is thus deflagrative (rather than detonative) in nature,[2] but depending on conditions can at times be quite violent. The casing offers the propellant grains some protection with respect to direct initiation by shock, but gives rise to additional thermal mechanisms by which the propellant can be ignited. These include hot particle ignition, friction and enhanced reaction buildup due to the confinement.

[19] Andersen, W. H., Irwin, L. J. and Louie, N. A., "Projectile Impact Ignition Characteristics of Propellants. II. Single, Double and Triple Base Propellants," Comb. Sci. and Tech. 20, 1 (1979).

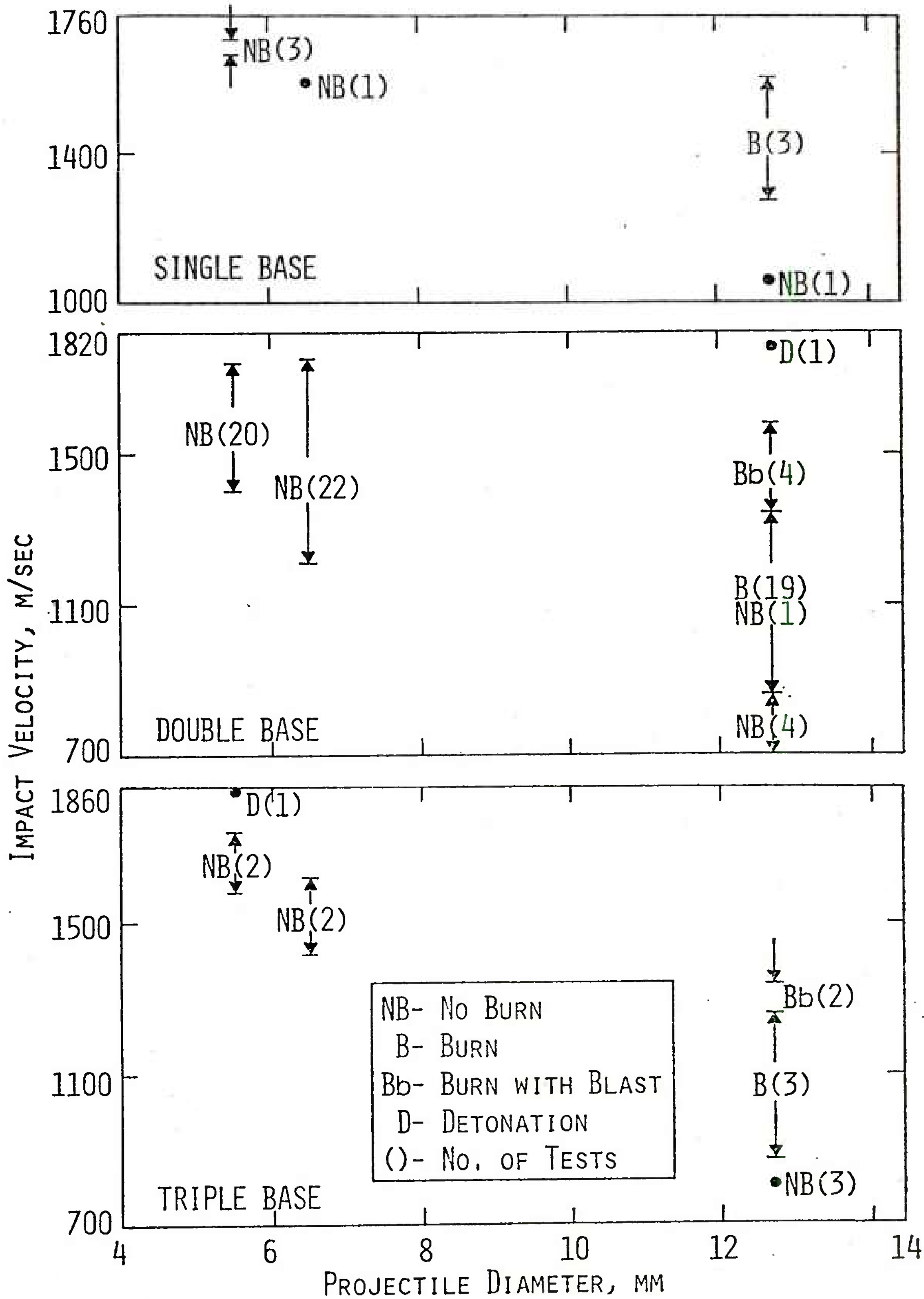

Figure 12. Impact Ignition Behavior of the Single, Double, and Triple Base Propellants.

It is useful to again recall that if the diameter of the propellant grains in actual use are smaller than the critical diameter of the propellant, then detonation will not propagate in the impacted propellant-no matter how intense the impact is. In this case the measured shock sensitivity of the larger diameter propellant has little relevance, although it may give some indication of the ease with which an impact can give rise to an energy-producing (but not propagating) reaction. A more valid indication of this type of reaction, however, would be obtained from impact measurements on the actual propellant grains themselves. This will be discussed further in section V.

4.3 Impact Pressure and Critical Ignition Energy

It has been shown[20] that the shock initiation to detonation of an explosive charge often appears to require that a certain critical energy per unit area, E_c, be delivered to the charge, where

$$E_c = Put = P^2t/\rho_o U = K \qquad (3)$$

P, u and U are the pressure, particle velocity and propagation velocity of the shock wave in the material, t is the duration of the shock pressure, ρ_o is charge density and K is an experimental constant for a particular charge (a simpler criterion sometimes used is $P^2t = K_1$). For a normal projectile (length greater than about 0.5 diameter), t is given approximately by

$$t = d/2C_p \qquad (4)$$

where d is projectile diameter and C_p is the lateral rarefaction wave velocity in the projectile.

The evaluation of Eq. (3) requires the shock Hugoniot of the propellant. This was not available, but was estimated for the LOVA-X1A propellant in ref. 15 using a density interpolation method. This method was based on the fact that the shock Hugoniot of a solid material (over a large range) usually depends largely on the density of the material, and very little on its composition. The resulting shock Hugoniot is shown in Fig. 13 (essentially the same results were obtained also by another independent method). The properties of the shock wave induced in the propellant by the brass projectiles at the various critical impact velocities were then estimated using the standard reflection method, and the results are shown in Table 5 and Fig. 13 (from ref. 15)(See footnote, page 32 for added discussion on the shock Hugoniot).

The shock pressures in Eq. (3), Table 5 and Fig. 13 correspond to the shock initiation pressure, P_i, of the propellant (discussed for the SSGT in section 3.3). Table 5 and Fig. 13 shows that P_i decreases with an increase in projectile diameter, and this occurs because the duration of the shock pressure in the propellant increases with an increase in diameter. The pressure is larger than for most conventional explosives because the propellant is relatively insensitive. For example, at a projectile diameter of 12.7 mm, some initiating shock pressures given in ref. 17 are: pressed

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[20] Walker, F. E. and Wasley, R.J., "Critical Energy for Shock Initiation of Heterogeneous Explosives," Explosivstoffe 17, 9 (1969)

TABLE 5, Critical Initiation Energies of the Propellant.

Projectile Diameter (cm)	V_i (m/sec)	P (kbar)	$Put=K$ E_c (cal/cm^2)	$P^2t=K_1$ E_c (cal/cm^2)
0.556	1665*	110	341	355
	(1727)**	114.8	370	387
0.65	1563	102.5	352	360
	(1622)	106	374	385
1.27	1392	86	511	496
	1240B***	74.8	398	375

* Lowest (Threshold) Impact Velocity for Detonation.

** Averaged Impact Velocities.

*** Threshold Impact Velocity for Burning.

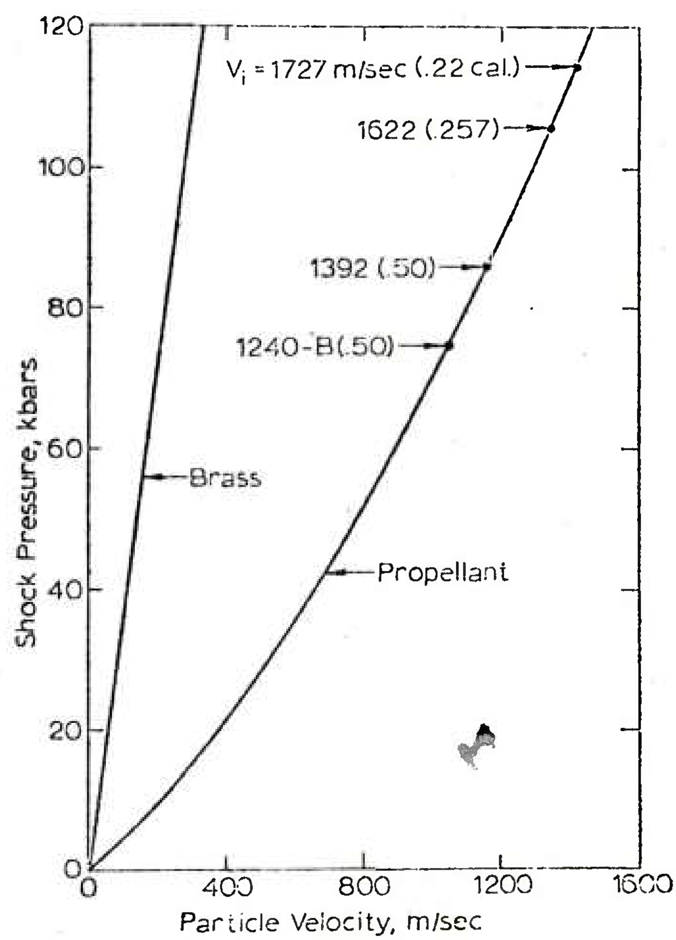

Figure 13. Shock Hugoniots, and Impact Properties of the LOVA-X1A Propellant.

PETN, 11 kbar; pressed RDX and tetryl, 22 kbar, and pressed TNT, 25-39 kbar. These values are for charges pressed to about 90% of crystal density. The initiation pressure decreases with a decrease in charge density.

The shock initiation pressure for cast explosives is much higher than for pressed explosives. For example, values given in ref. 17 and 18 for a 12.7 mm diam. projectile range from about 21-96 kbar for Composition B, and 37-110 kbar for cast TNT. An assessment of the relative sensitivity of the LOVA-X1A propellant as compared to these two cast explosives based on pressure depends on the data selected for comparison. Generally speaking, the same conclusions are obtained as were arrived at on the basis of relative critical impact velocity (discussed before), since the initiating impact pressures are derived from the critical impact velocities. It is of interest to note that the critical initiating shock pressures for the LOVA-X1A propellant derived from the projectile impact tests (Table 5), are a little lower than the value (145.3 kbar) derived from the scaled SSGT experiments (Fig. 9). This implies (from Eq. 3) that the effective time duration of the shock in the gap test was a little smaller than in the projectile impact tests.

Table 5 shows that the critical energy criterion, Eq. (3) (also the simpler criterion), was obeyed for the ignition, but not the detonation threshold curve in Fig. 10. This is of some significance, and provides quantitative support for the postulated model, since the time in Eq. (4) was assumed to define the ignition (and not the detonation) time of the impact reaction. However, if it is assumed that a longer sample length (in the impact tests) would allow the ignited propellant to build up to detonation at the larger projectile diameters (discussed previously), then the detonation threshold of the propellant is reduced to the ignition threshold, and the critical ignition criterion is also valid for the detonation reaction (this could explain various discrepancies in the literature regarding the experimental validity of Eq. 3).

With this assumption, the shock sensitivity of the LOVA-X1A propellant can also be compared with other explosives on the basis of critical energy.* Table 5 shows the values obtained using the projectile impact data. The average value obtained ($\sim$375 cal/cm^2) is significantly larger than values given in ref. 15 for conventional explosives, e. g., pressed TNT = 34, Comp. B = 36 and cast TNT = 100 cal/cm^2. This shows that a much larger shock energy is required to initiate the propellant than the explosives.

Thus, from the results obtained from all of the preceding methods of evaluating shock sensitivity (card gap test, critical projectile impact velocity, critical pressure and critical energy) it is concluded that the LOVA-X1A propellant is quite insensitive to the initiation to detonation compared to most conventional explosives and propellants being used at the present time.

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*Subsequent to the completion of this report, an experimentally-determined shock Hugoniot of the LOVA-X1A propellant was obtained from V.M. Boyle, BRL[21]. It was found that over the range of interest the experimental Hugoniot differed only slightly from that given in Fig. 13, and the computed critical energies differed very little from those given in Table 5.

SECTION 5

IMPACT SENSITIVITY OF STACKED GRAINS

In Section 4 a summary was presented of the projectile impact characteristics of solid cylinders of the LOVA-X1A propellant, 1.5 in. diam. x 0.75 in. thick. It was shown that depending on the impact velocity, the material can undergo either a detonation or a burning-type reaction (at sufficiently low velocities the impact produced fracture of the sample without inducing a sustained reaction). However, the individual grains of propellant used in a gun are much smaller than the preceding disks and consequently cannot undergo a propagating detonation on an individual basis if their diameter is less than the critical diameter of the propellant. Thus it was shown in section 2 that a bare, 0.245 in. diam. grain of the LOVA-X1A propellant will not propagate detonation, and that the same grain confined in a 0.375 in. thick brass casing will only occasionally support detonation if strongly initiated (the critical diameter of grains of this diameter with perforations is not presently known).

5.1 Potential Differences of Disks vs Stacked Grains

On the other hand, when individual grains of propellant are stacked adjacent to each other there is the possibility of cooperative and porosity effects on the impact initiation of the propellant. This could alter the impact initiation characteristics of the propellant from that obtained with the solid disks. Some potential differences between the impact initiation characteristics of the solid disks and stacked grains are illustrated in Fig. 14. As shown in Fig. 10 and discussed in Section 4.1, the projectile impact of solid disks (1.5 in. diam. x 0.75 in. thick) of LOVA-X1A propellant can produce either the detonation or burning of the propellant. The impact velocity threshold for inducing burning (ignition) is lower than that for inducing detonation at large projectile diameters, and at small projectile diameters the burning threshold merges with the detonation threshold. This behavior is shown by the solid lines in Fig. 14. It was also discussed earlier that if the length (thickness) of the impacted disks is made larger, the detonation threshold curved may also merge with the ignition threshold at the larger projectile diameters.

Now consider the potential impact behavior of stacked grains. Depending on the grain size and geometry, and the particular manner in which the grains are stacked, there will be various localized concentrations of porosity and many free surfaces among the grains. The porosity (between adjacent grains) may have a sensitizing effect on the impact initiation characteristics of the material. This would reduce the velocity threshold for producing burning at any particular projectile diameter, as illustrated by the dotted line in Fig. 14. It could also reduce the impact velocity threshold for producing detonation (shown by curve P), as well as allow detonation to propagate in the stacked grains, even though the diameter of an individual grain is less than the critical diameter of the propellant (the detonation in the stacked grains would be analogous to the detonation of a porous charge). On the other hand, the presence of the free surfaces of the individual grains may simultaneously (along with the enhanced ignition resulting from the voids between grains) allow more rapid energy loss by rarefaction,

and if this effect were dominant the threshold for the detonation reaction may be greater than that of the disks, as illustrated by curve R. The particular manner in which the grains are stacked would be expected to have some effect on the impact initiation characteristics, depending on the impact conditions.

5.2 Experimental Tests

Experimental tests were conducted to obtain information regarding the behavior and sensitivity of stacked grains of the LOVA-X1A propellant to projectile impact. The tests consisted in shooting flat nosed brass projectiles into a stacked bed of propellant grains at different velocities, and observing the impact reaction by means of an open shutter camera, a photocell, post inspection of the impact event, and weighing of the propellant fragments. The apparatus used was the same as used for the projectile impact studies of solid disks of the propellant (described in ref. 15, 19 and summarized in Section 4). Figure 15 shows the instrumented target box. The stacked bed of grains (to be described) was supported on a U-shaped cradle mounted on a rod at the test sample position. A rim prevented the bed from being pushed through the cradle. The entering projectile passed through the velocimeter tube (which measured its velocity), impacted with and passed through the propellant bed, and exited the box at the exit port. The light emitted by the impact reaction was recorded by an open shutter camera and photocell circuit, which provided information regarding the nature of the reaction (discussed in ref. 15). After a test. the fragments from the bed were swept into a collection tube mounted in the floor of the box, where they were removed for weighing.

Two different size beds of stacked propellant grains were used in the tests. The smaller bed was used for the small diameter (.22-and .257-caliber) projectiles, and the larger bed was used for the large (.50-caliber) projectiles. The small stacked bed of grains (shown in Fig. 16) was prepared as follows. Extruded strands of solid LOVA-X1A propellant (ave. diam. about 0.245 in., discussed in Section 2) were cut into 0.5 in. long lengths, and stacked inside a box (1 in. x 1 in. x 0.75 in., inside dimensions). The box was made of 1/4 in. thick plywood on four sides (glued together), Plexiglas (1/4 in. thick) on one side (for observation by the camera and photocell), and the front end (exposed to the impacting projectile) was covered with cellophane. The grains were stacked in three layers, with eight grains in a layer (giving a total of 24 grains), as shown in Fig. 16. Cardboard was inserted between the grains and the box (where it was needed) to maintain firm contact between the grains.

In the large box, the inside dimensions were increased to 1.5 in. x 1.5 in. x 1 in., and 72 individual grains were used in a test. The box contained 6 grains in each of its crosswise directions, and 2 deep as with the smaller box.

5.3 Experimental Results

The results of the projectile impact tests are summarized in Table 6 (these tests used up all of the available propellant samples). At the smaller (.22 and .257 caliber) projectile diameters, the tests gave very little evidence of any sustained reaction being induced in the propellant grains as the result

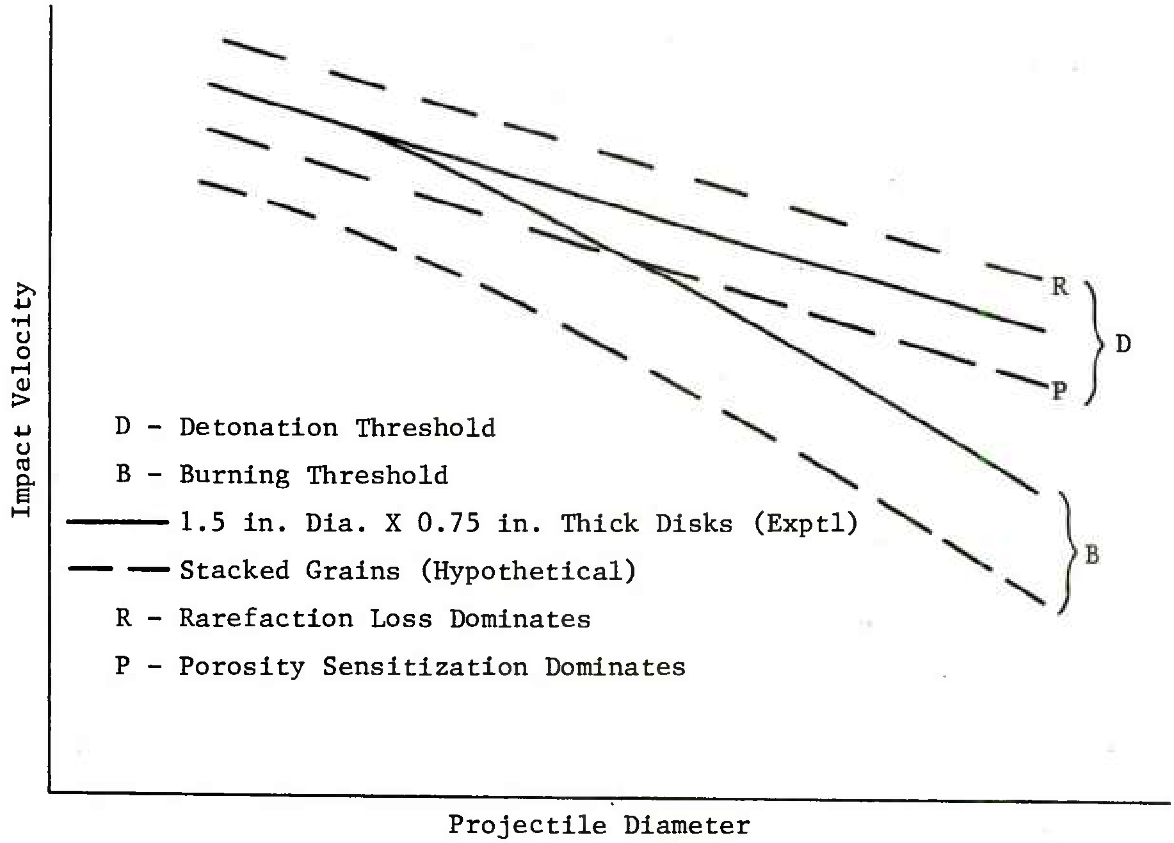

Figure 14. Potential Differences Between the Projectile Impact Initiation Characteristics of Solid Disks and Stacked Grains of Propellant.

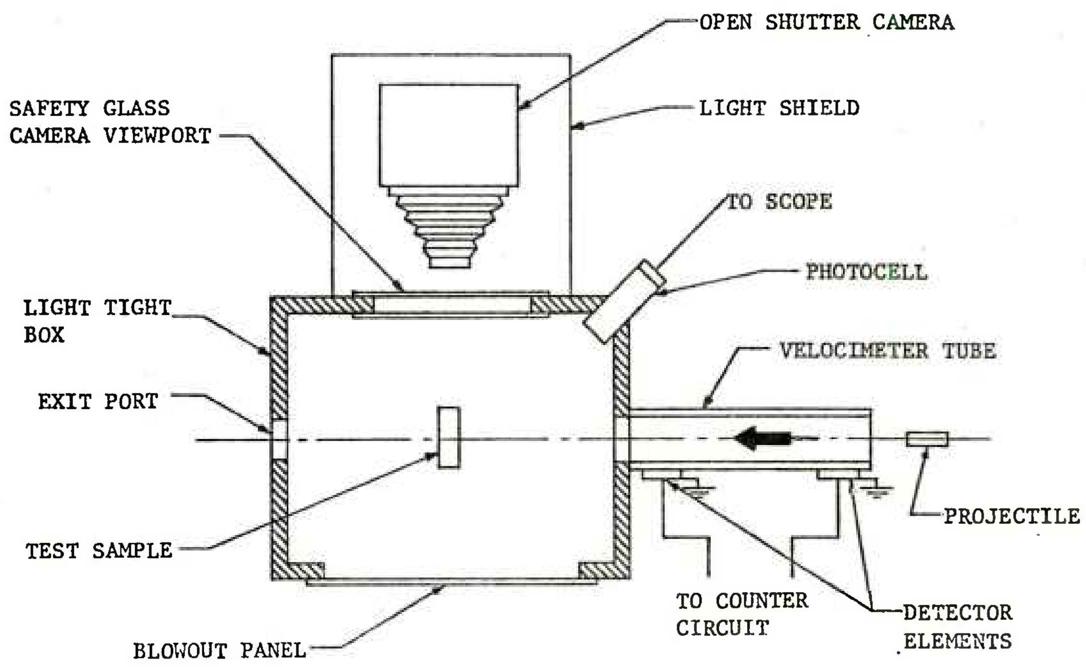

Figure 15. Instrumented Target Box for the Projectile Impact Tests.

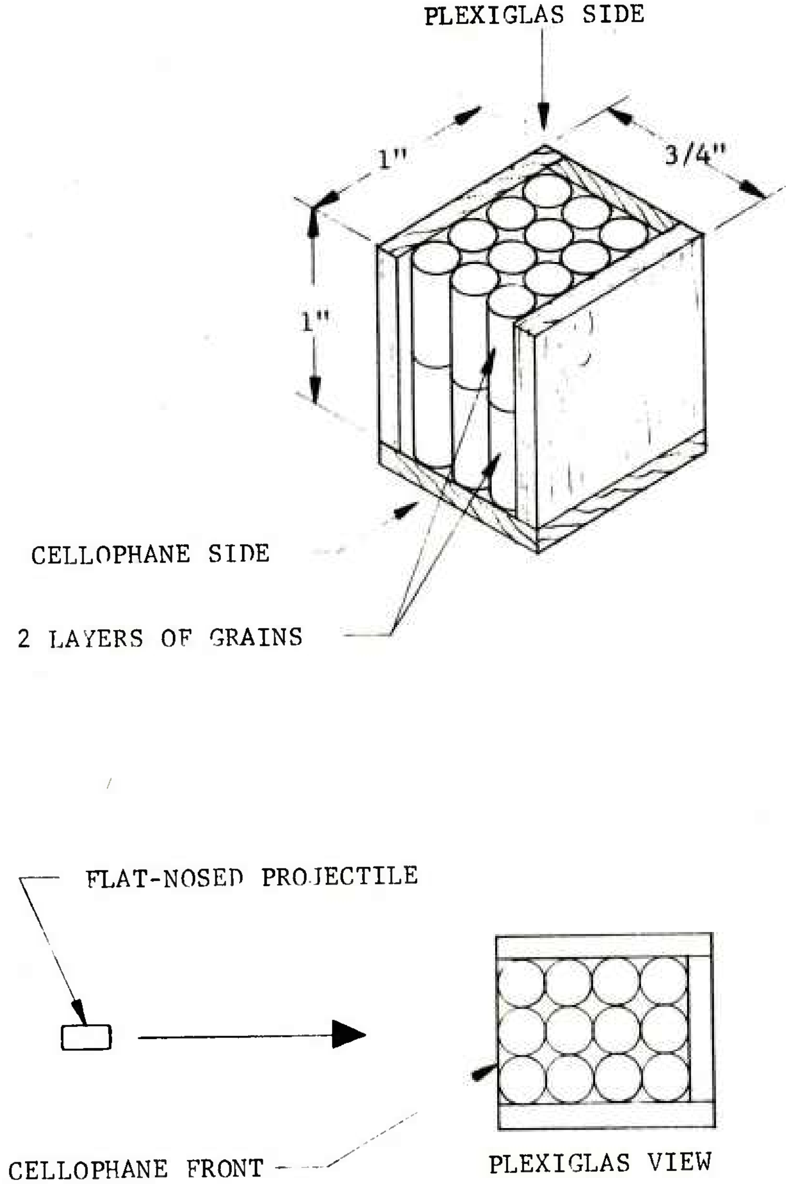

Figure 16. Procedure for Determining the Impact Initiation Characteristics of Stacked Grains of Propellant (Small Box).

TABLE 6. Response of Stacked Grains of the LOVA-X1A Propellant to Projectile Impact

Projectile Diameter (in.)	Projectile Velocity (ft/sec)	Propellant Consumption (Wt%)	Impact Response
0.22	4831	8	No flashing, sparking or reaction
0.257	5155	39 ?	Impact flash, no reaction (black photo)
0.257	5848	27 ?	Flash and sparking, minor localized reaction
0.257	5917	--	Impact flash, no reaction
0.50	4032	32	Burn reaction (white photo), no pressure buildup
0.50	4630	34	Burn reaction, no pressure buildup
0.50	4808	42	Burn reaction, no pressure buildup
0.50	4975	57	Burn reaction, no pressure buildup
0.50	4950	85	Burn reaction, burnt wood and plastic, no pressure buildup
0.50	5102	64	Burn reaction, no pressure buildup

of impact. At the single impact velocity studied (4831 ft/sec) using the 0.22 in. diam. projectile, no light was emitted by the impact that was detected by the sensors. For the higher impact velocities (5155, 5848, 5917 ft/sec) using the 0.257 in. diam. projectile, the photocell records gave the rise and decay pattern that was characteristic (in the disk tests) of an impact flash, without any sustained reaction occuring. The photographic records showed the flash in two of the tests, and in addition showed one or more broad streamers which indicated some sparking. The test at 5848 ft/sec gave some evidence of some very minor localized reaction, but in general all these four tests gave a light output (detected by the sensors) that was characteristic of what has been called a No Burn reaction in the previous studies conducted in these laboratories.[15] A comparison of the impact velocities used in these tests with the velocities used in the disk studies (Fig. 10) shows that the velocities used for the 0.257 in. diam. projectile were all larger than the threshold value (5100 ft/sec) necessary to produce detonation in the disks. However, detonation was only produced about 50% of the time in the disks, with the other impacts resulting in a No Burn reaction.

On the other hand there seemed to be a significant weight consumption of the propellant as the result of impact in two of the 0.257 in. diam. projectile impact tests (marked with question marks in the table). This consumption is not believed to have been real in those two tests, and probably resulted from weighing error. In the tests, the impact caused a considerable amount of small sized debris consisting of wood and Plexiglas fragments and powdered propellant, in addition to the larger, easily separated materials. Sieving of the debris is believed to have caused some unburned propellant powder to escape being weighed. Particular attention was given to the problem in later tests. Thus the present belief is that projectile impact at the small projectile diameters (0.22 and 0.257 in.) caused very little if any reaction in the stacked grains of the propellant.

At the large projectile diameter (0.5 in.), however, the impacts resulted in a burning type of reaction being induced in the propellant over the entire impact velocity range studied (4032-5102 ft/sec). The reaction was characteristic of that found for the disks over a more limited velocity range (4070-4590 ft/sec). The photographic records were completely white (overexposed), as was found in the disk studies, and the photocell records gave no decay after the initial rise (the photocell was not used in all of the tests). Also, several tens of percent of the propellant was consumed, as was the case for the disks. In no case was a detonation produced, or any indication of a violent reaction (e.g., non-detonative blast), even though the higher impact velocities used were significantly larger than the threshold found for detonation (4590 ft/sec) in the disks (Fig. 10). In one test (4590 ft/sec) there was physical evidence of some burning of the corners and edges of some of the wood and plastic box fragments, as well as some of the cardboard used for packing. The lowest velocity tested (4030 ft/sec) produced the burning reaction, but this velocity is essentially the same (4070 ft/sec) as the burning threshold for the disks.

In all of the tests (Table 6), all of the propellant grains were broken as the result of impact except for 3 grains in the 5848 ft/sec test, 2 grains at 5917 ft/sec and 1 grain at 4630 ft/sec.

The available evidence (including photocell response) indicates that the burning induced in the propellant by the large (0.50-caliber) projectiles probably resulted from shock compression, as in the case of the disks. Since a burning was induced in the solid disks over the velocity range of 4070-4590 ft/sec, there is little reason to believe the mechanism should change over this range for the grains. On the other hand, at higher velocities the larger disk samples underwent detonation, but only burning was observed for the grains. This resulted because the smaller grains were incapable of propagating detonation on an individual basis. Mechanisms other than shock compression (e.g. friction, shear or adiabatic gas heating) can in principle also cause the ignition of an impacted material. It would be expected, however, that these mechanisms would be more significant under lower velocity conditions when direct shock compression is ineffective. Unfortunately the lowest projectile velocity used for the stacked grains was about the same as used for the disks. It is therefore not known whether the stacking sensitized the propellant to impact at this projectile diameter, or whether other mechanisms might be operative. However there was little evidence that stacking sensitized the propellant at the small projectile diameters. It would be expected that if other mechanisms were operative, the effect would be especially significant at small projectile diameters where the time available to ignite the propellant by shock is very small.

Thus the evidence indicates that the impact of stacked grains of the propellant with a large (0.5 in diam.) projectile produces a burning of a portion of the propellant, but the reaction is non-detonative and non-violent up to very high impact velocities (5100 ft/sec).

SECTION 6

CONCLUSIONS

The results of this investigation have shown that the critical diameter of the bare LOVA-X1A propellant is quite small(between 0.245 and 0.375 in.), and hence that detonation cannot propagate in individual propellant grains whose diameter is about 0.25 in. or less. For a larger diameter charge where detonation can propagate (once initiated), the propellant is relatively insensitive to initiation compared to most explosives and propellants in use today. This was shown on the basis of its empirical sensitivity to shock initiation by card gap and projectile impact tests, as well as from the critical initiation pressure and critical initiation energy derived from the tests. It was also shown that the response of stacked grains of the propellant to projectile impact is deflagration (and not detonation) up to the highest impact velocities tested. The stacking of the grains appeared to have little affect on the ignition sensitivity (compared to larger solid disks) of the propellant at small projectile diameters (information regarding the relative threshold sensitivity was not obtained at the large (.50-caliber) projectile diameter).

6.1 Recommendations

The results of this program have elucidated many aspects of the detonability characteristics of the LOVA-X1A propellant, and provided a basis for additional studies that should be conducted to further determine the safety aspects (with respect to detonation) of both this particular propellant, and other propellants of the LOVA-type. Of special importance along these lines, would be experiments that would simulate and define the nature of the reaction (and its buildup behavior) in a metal-cased bed of propellant grains that is impacted by a high velocity projectile. In particular, the possibility of a DDT (deflagration to detonation transition) should be elucidated. Experiments of this nature could be conducted by placing the grains in an instrumented metal tube, and subjecting the tube to projectile impact. The impact reaction would be studied as a function of the various factors (e.g., impact velocity, and properties of the tube and propellant grains) that may control the event.

The effect of small perforations in propellant grains (such as are used to help control the burning characteristics) on the critical diameter of the grains, and the impact sensitivity of stacked grains should also be established. These tests would be conducted in the same manner as the solid grain experiments discussed in this report. Finally, it would be desirable to conduct detonability tests such as discussed in the report (and above) on propellants having other compositions than the LOVA-X1A propellant. These tests together with the results of the LOVA-X1A propellant, would then allow estimates to be made on other propellant compositions, which would greatly reduce the time and cost necessary to evaluate the sensitivity and safety of these compositions for potential use.

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